Beyond Maps: Using GIS to Identify Models and Evaluate Trade-offs in Fisheries Science

Paul Rago, Steven Murawski, Susan Wigley, and Charles Keith
NMFS Northeast Fisheries Science Center

Abstract

Much of fisheries science deals with the analysis of spatially-distributed resources harvested by mobile fleets. Seasonal movements of fishery resources and targeting of fishing effort on localized abundance concentrations are well-known features of fisheries. The spatial aspects of fisheries induce heterogeneity in the relationship between fishing effort and fishing mortality, and may have important biological implications for stock productivity. Yet these considerations infrequently enter models to estimate abundance or to evaluate the efficacy of alternative harvesting policies. GIS methods can be used to improve the realism of population models and also to evaluate trade-offs inherent in any fishery policy. One of the most difficult aspects is the identification of the appropriate level of spatial and temporal resolution. The appropriate resolution must not only address the salient features of the underlying process but also be supported by the available data. Deviations from this norm will result in either interesting dynamic models without data or biased models with overly aggregated data. GIS models can also be used to develop static models illustrating tradeoffs among competing objectives. Simultaneous maximization of yield, reduction of bycatch, and minimization of habitat impacts are not possible. Appropriate use of GIS methods can be used to evaluate the consequences of alternative spatial patterns of harvest that can be robust to alternative weightings of competing objectives. Example cases of model improvements and trade-offs, drawn from analysis of scallop and groundfish fisheries in the Northeast, will be used to illustrate potential improvements to existing methods.

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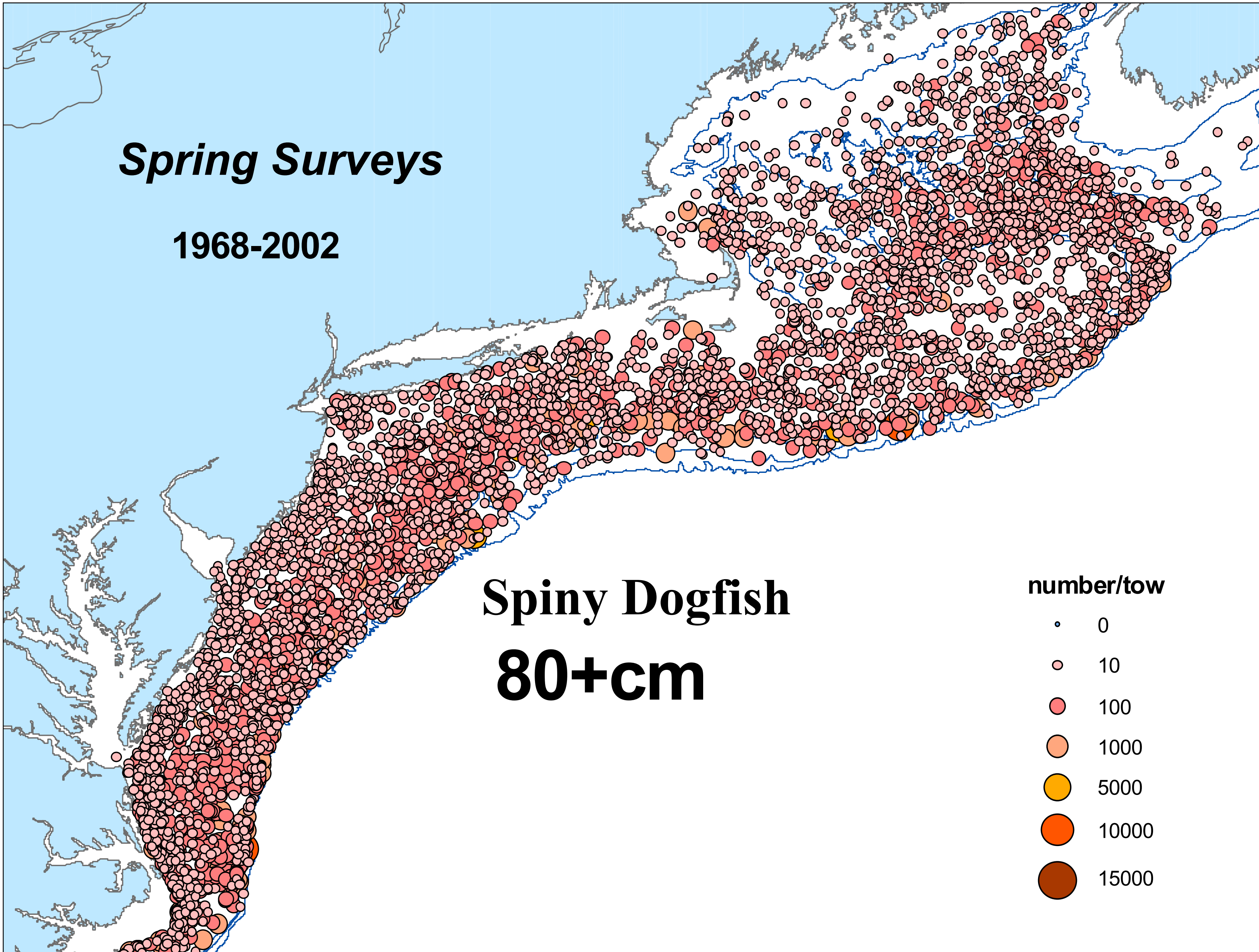
Woods Hole
September 9, 2004


Spring Surveys
1968-2002
Spiny Dogfish
80+cm
number/tow
0
10
100
1000
5000
10000
15000

Objectives

- Implications of Spatial data for assessments and management

✓Models
✓Data and Assessment
✓Fisheries Management

✓Measure with Micrometer
✓Mark with Chalk
✓Cut with Ax

- Spatial Resolution
- Using GIS to guide formulation of Dynamic Models
- Trade-offs

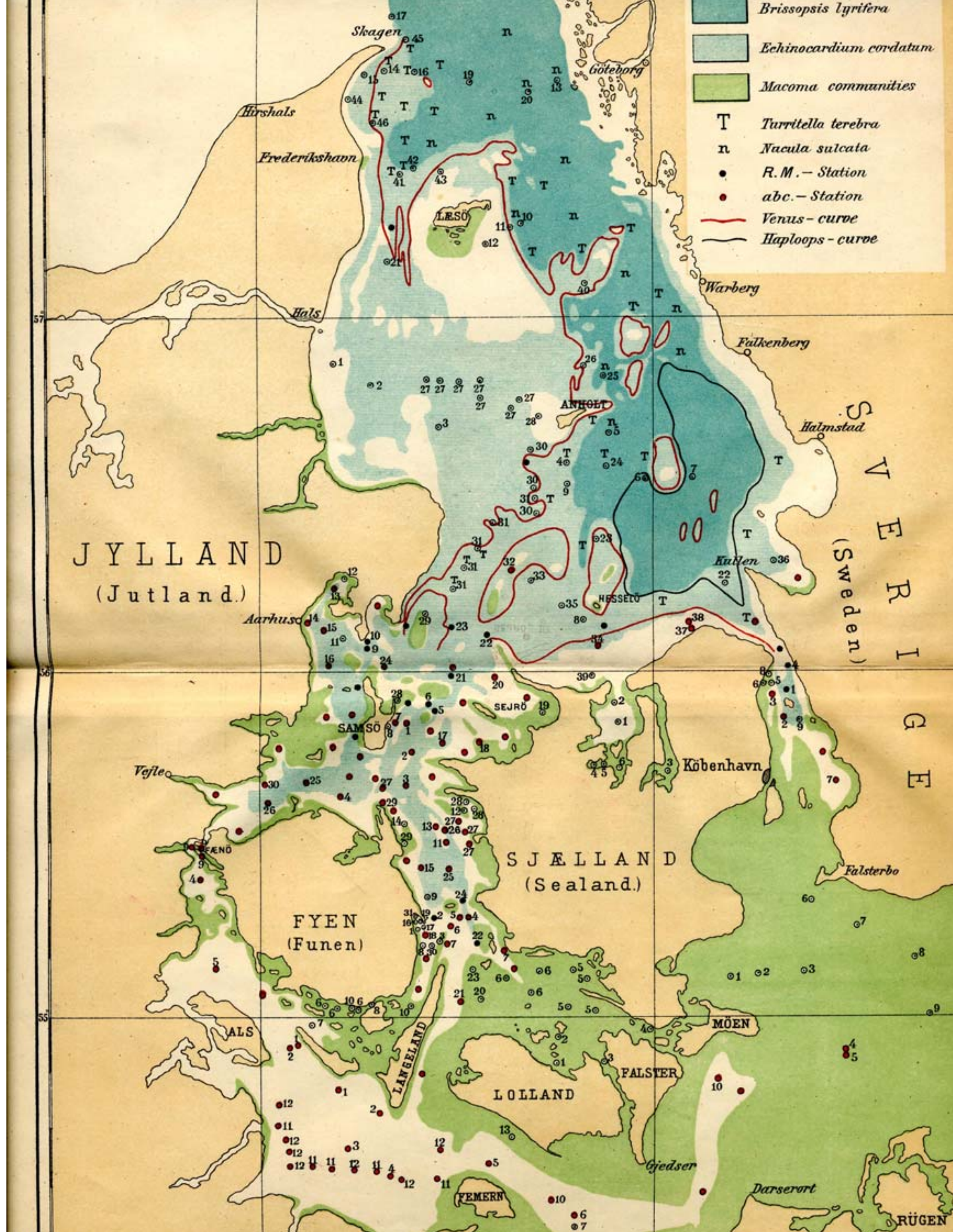
"life does not stand still while specialists put their minds in order"

Michael Graham, 1950. Address to United Nations

GIS has a long history.

- Advances in population estimation methods.
- Allocation of resources among jurisdictions
- Management demands
  - Season and area closures
  - Effects of gear changes
- Ecosystem monitoring
- Habitat identification

Peterson, C.D.J. 1918. The Sea Bottom and its Production of Fish-Food. Rep. Danish Biological Station. 25.
Activities from 1883-1917



Importance of Heterogeneity in Stock Assessment Models

- Catch= Fishing Mortality * Biomass

- *Effort constant over time and space*
- ***$C(t)=F\ B(t)=q\ E\ B(t)$***

- *Effort as a function of time*
- ***$C(t)=q\ E(t)\ B(t)$***

- *Effort as a function of time and space*
- ***$C(x,y,t)=q(x,y,t)\ E(x,y,t)\ B(x,y,t)$***

Perspective on Spatial Dynamic Models

"…indications at the present time are that neither knowledge of the mechanisms of dispersion nor accuracy of data and commercial statistics is sufficient to justify the labour involved in rigorous treatment…[but] the method enables working solutions to be obtained."

R.J. H. Beverton and S. J. Holt, 1957

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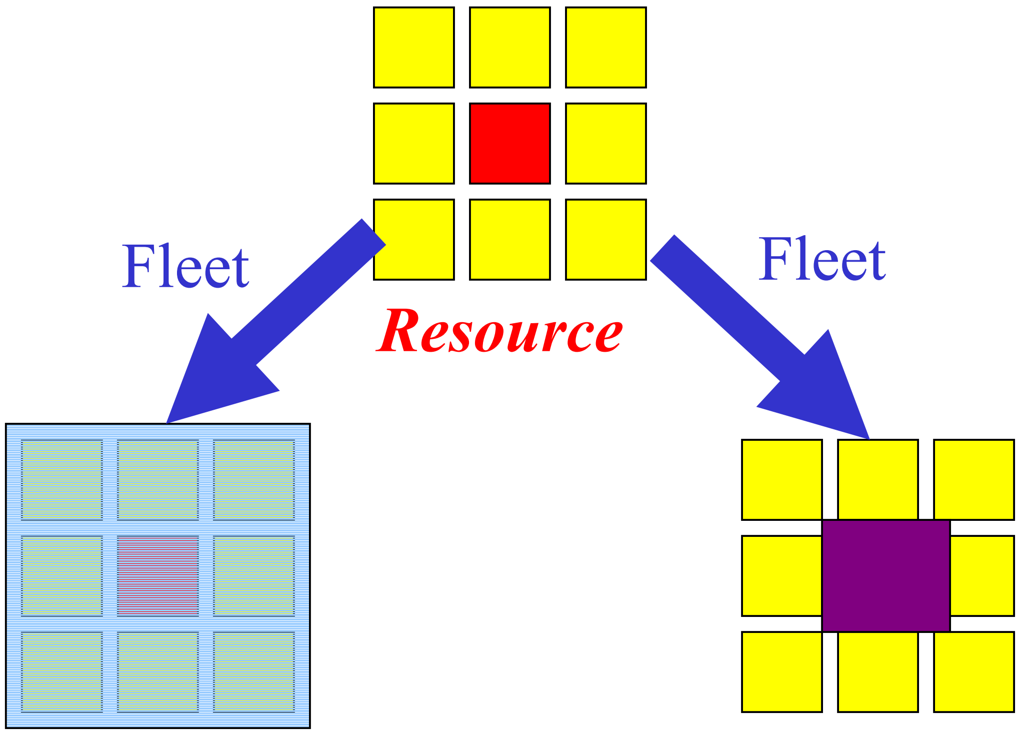
R.J. H. Beverton and S. J. Holt, 1957

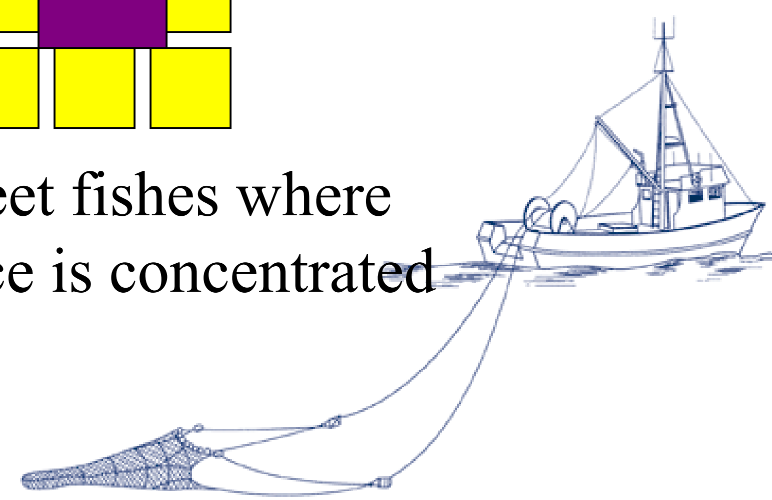
First known occurrence of the expression "good enough for government work" in the fisheries literature.

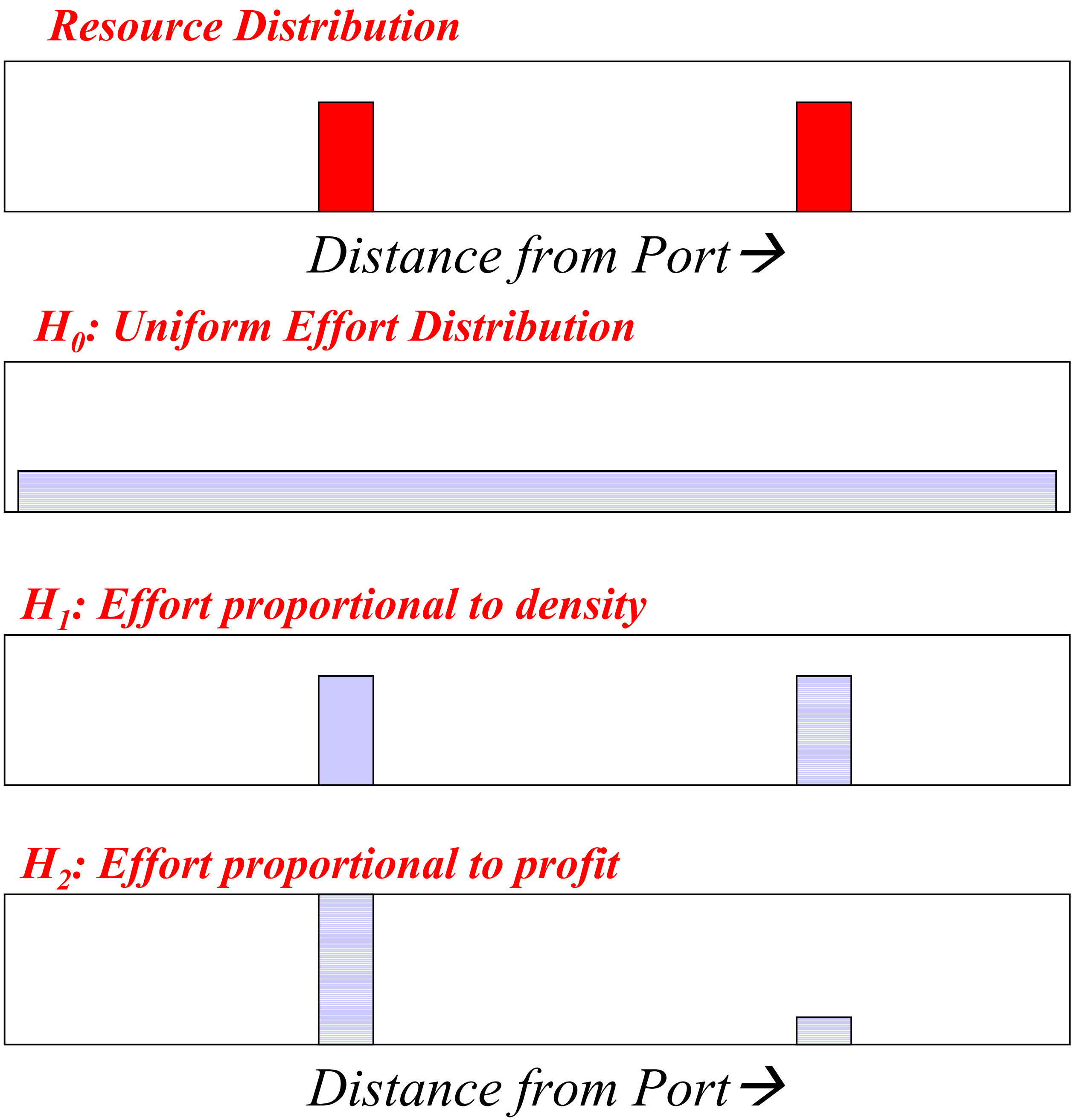
Consider a spatially distributed resource subjected to harvest by a mobile fleet.



***H_0*: Fleet fishes uniformly over entire area of resource

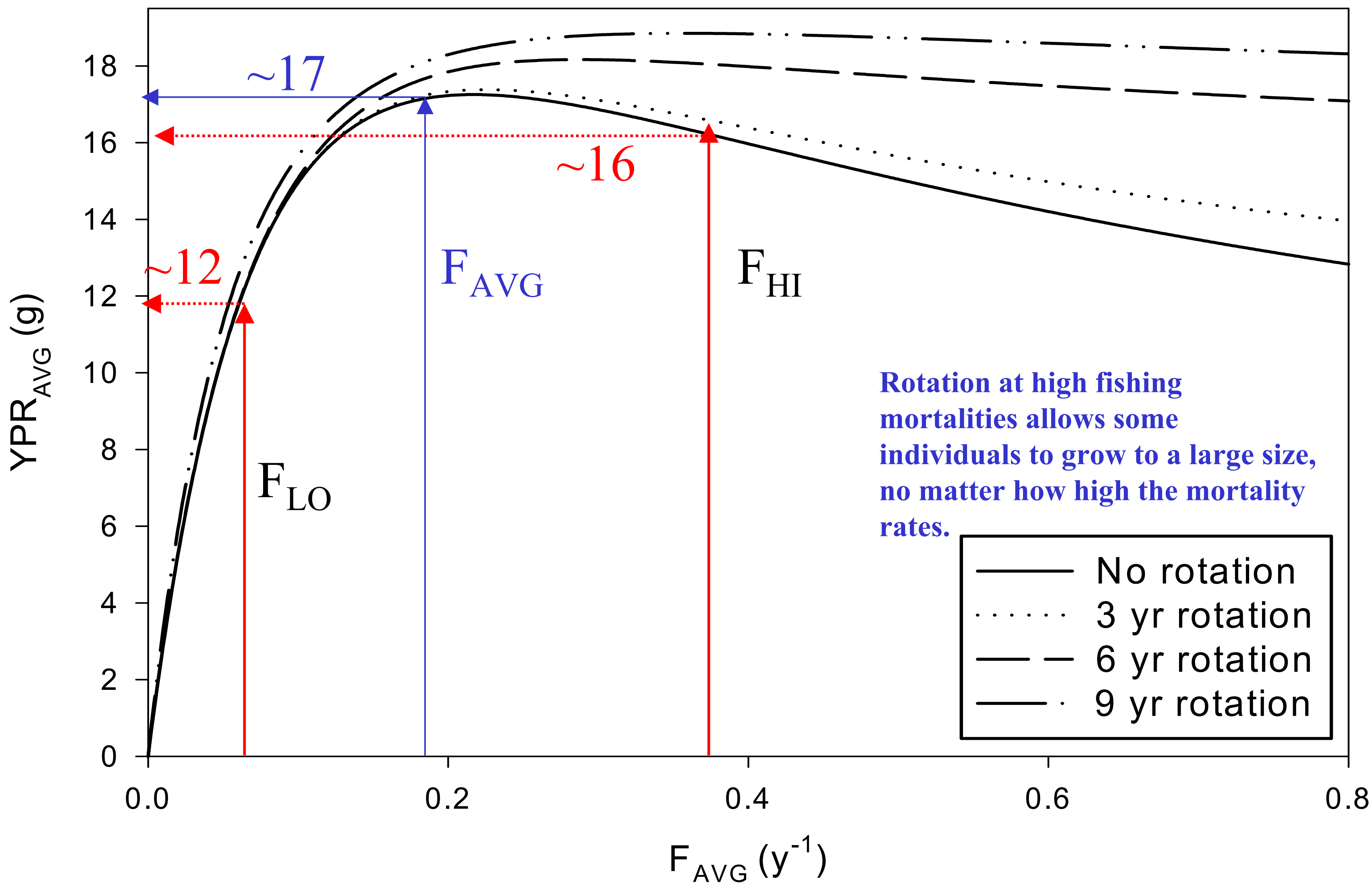
***H_1*: Fleet fishes where resource is concentrated





Consider the effects of joint effects of cost and resource distribution on fishing mortality

Yield per Recruit: Effects of heterogeneous fishing—Jensen's Inequality



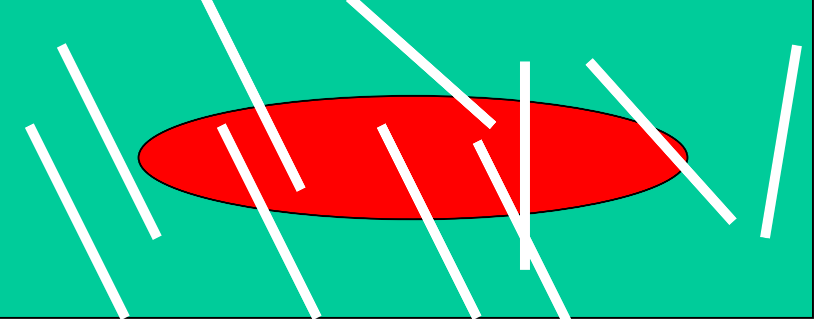
Estimating Migration from Simple Tagging Experiments?

Consider release of tags in area A and B. Tags recaptures are voluntarily returned by commercial harvesters. Suppose 90% of the tags released in Area A are recaptured in Area B.

	Area A	Area B
Releases	1000	1000
Recaps in same Area	10	5
Recaps from Area A	---	90
Recaps from Area B	1	---

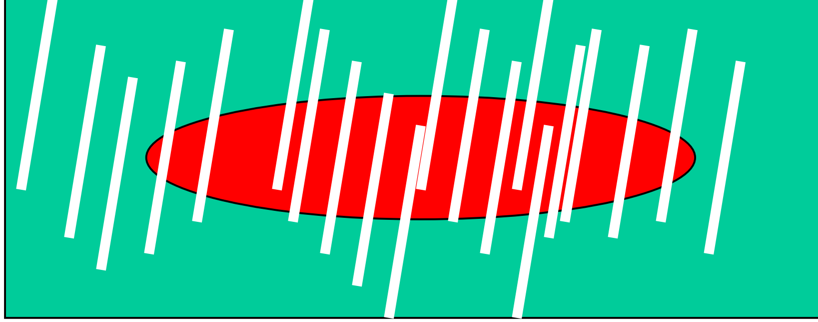
Possible Explanations

1. High migration rate from A to B.
2. High fishing rate in Area B
3. Low reporting rate in Area A
4. Low initial survival of releases in B
5. All of the above



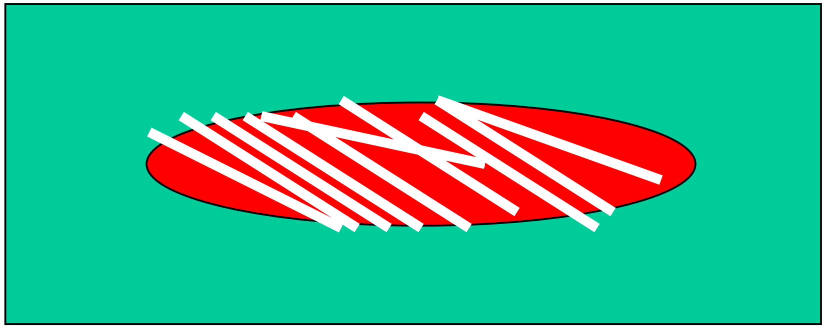
Effort Constant and No targeting

Fixed Cost
High Bycatch
Low CPUE
High Habitat Impact



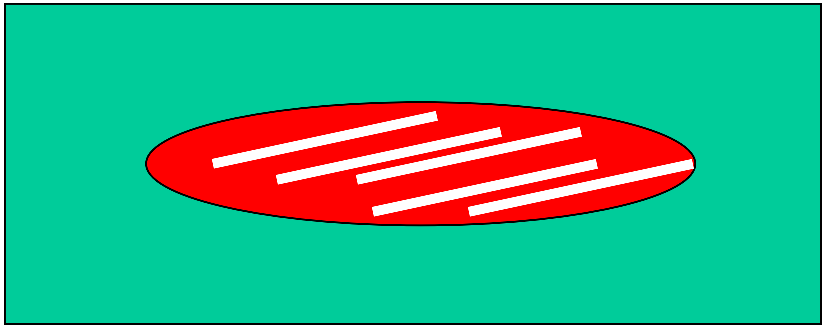
Quota and No targeting

High Effort
High Bycatch
Low CPUE
High Habitat Impact



Effort Constant and Targeting

Excessive Mortality
Low Bycatch
High CPUE
Low Habitat Impact



Quota and No targeting

Lower Effort/Cost
Low Bycatch
High CPUE
Low Habitat Impact

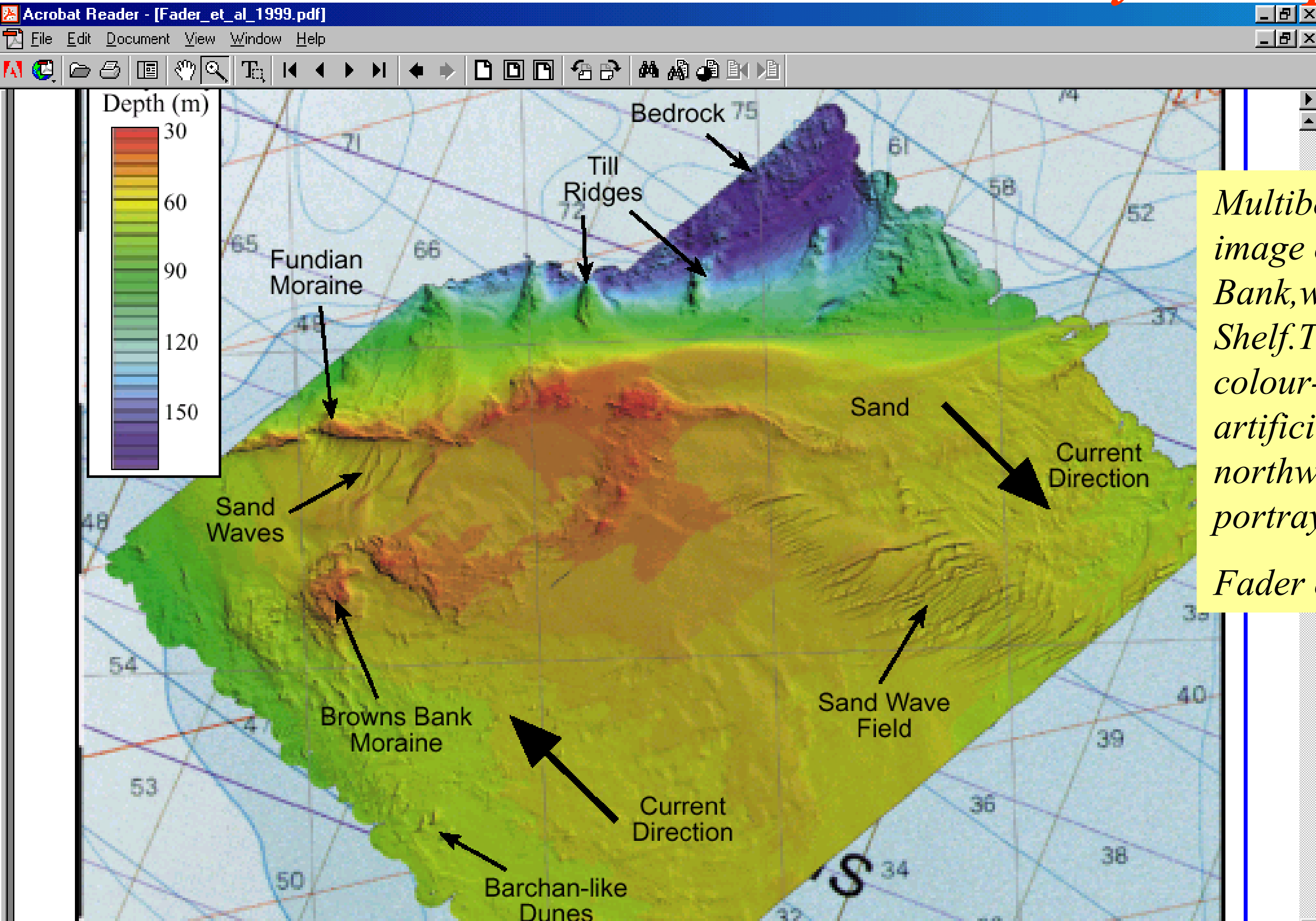
Problems of Inference

- If we ignore the spatial implications of fisheries data in our models we run the risk of maximizing the likelihood of the least likely model—model misspecification.
- If we develop realistic but inestimable models our conclusions are solely the deducible products of our assumptions—interesting but infrequently useful.

Non spatial Model		**Spatially-distributed Model**
Data Space→Parameter Space	↔	Data Space→Parameter Space
One to One Relationship		***One to Many Relationship***
Probably wrong		*Some may be right*

- Therefore
  - Develop models consistent with data to support
  - Use ancillary data where possible—e.g., "smart" tags
  - Exploit embedded experiments—e.g., closed areas

Advanced Imaging Systems: multi-beam, photographic, laser line scanner, ...Ground-truth by samples

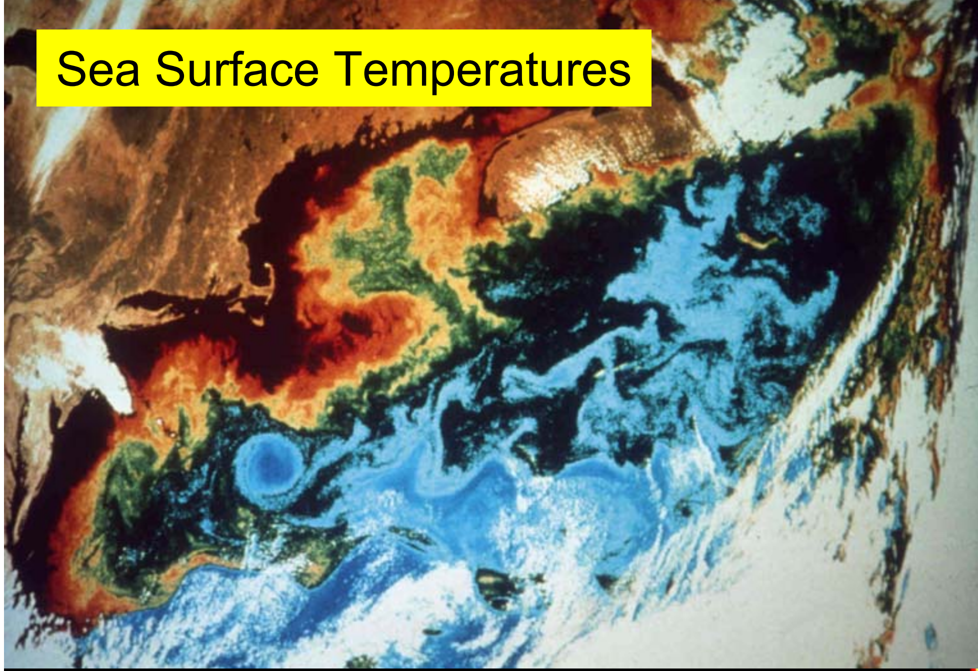


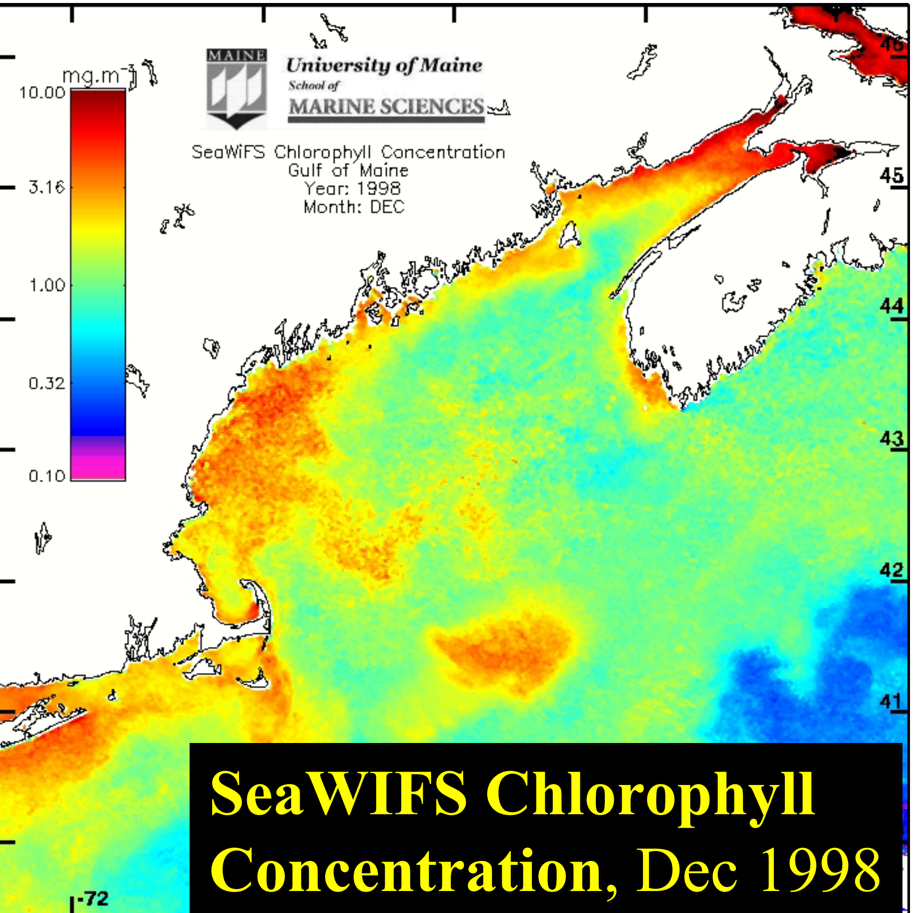
Multibeam bathymetric image of western Browns Bank,western Scotian Shelf.The image shows colour-coded depths and is artificially-shaded from the northwest to enhance the portrayal of morphology.

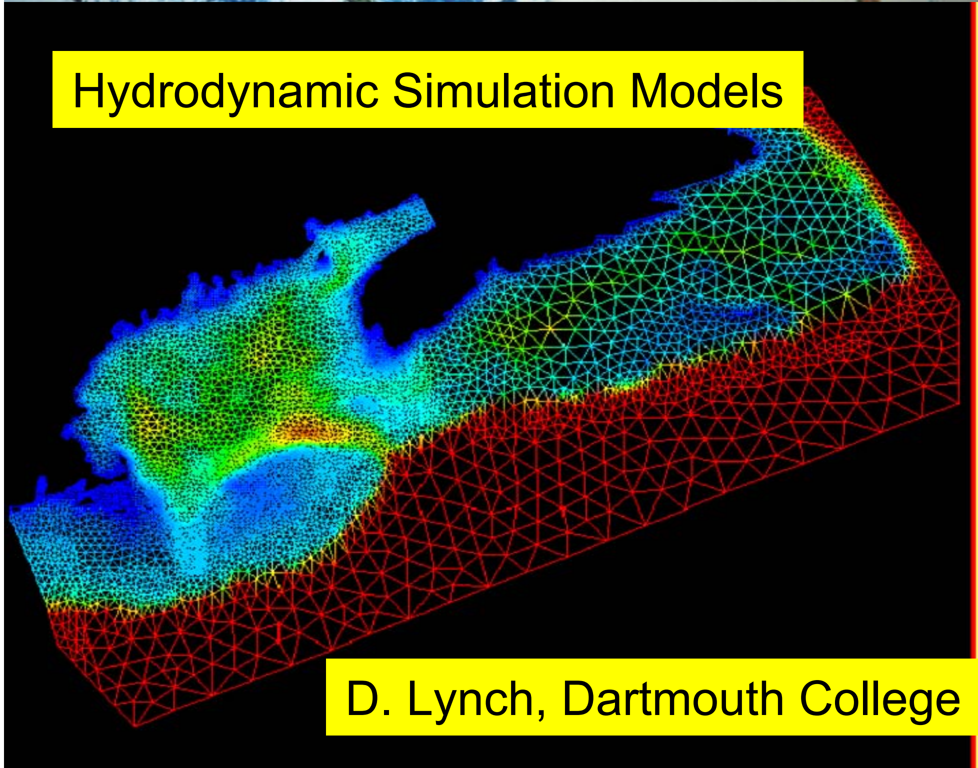
Fader et al.

Planning for the future

Integration of Fish Distribution with synoptic data sets

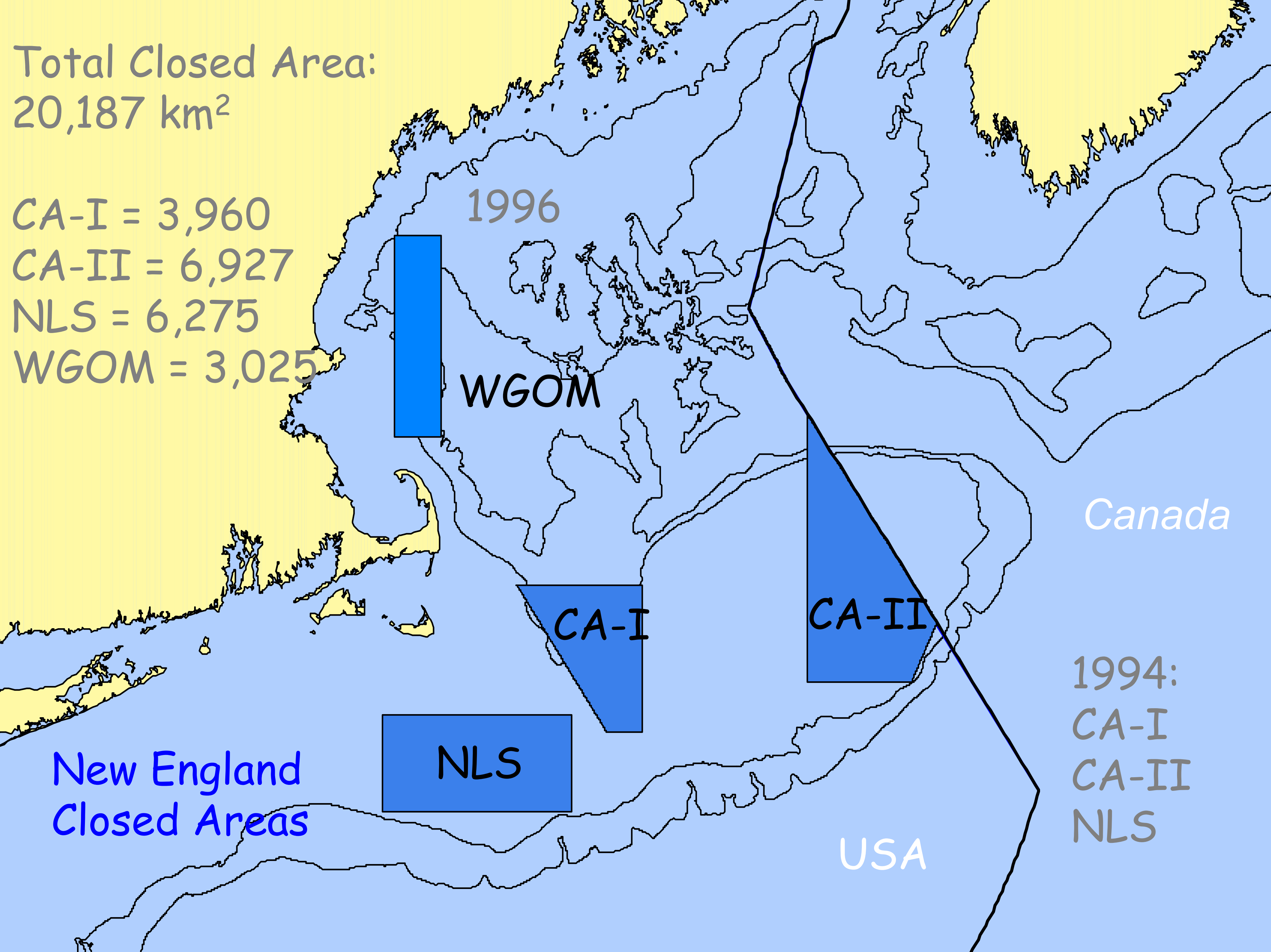




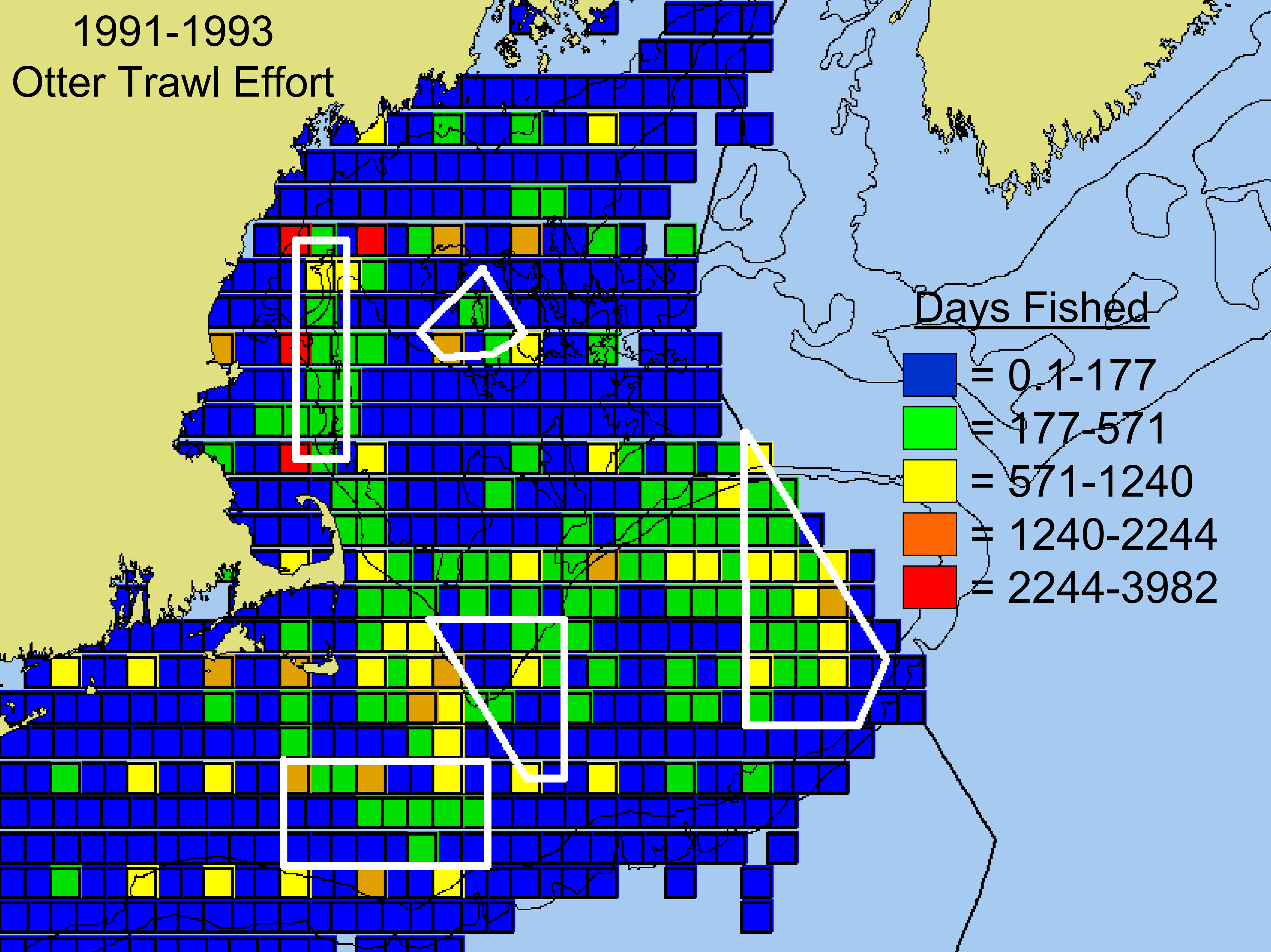


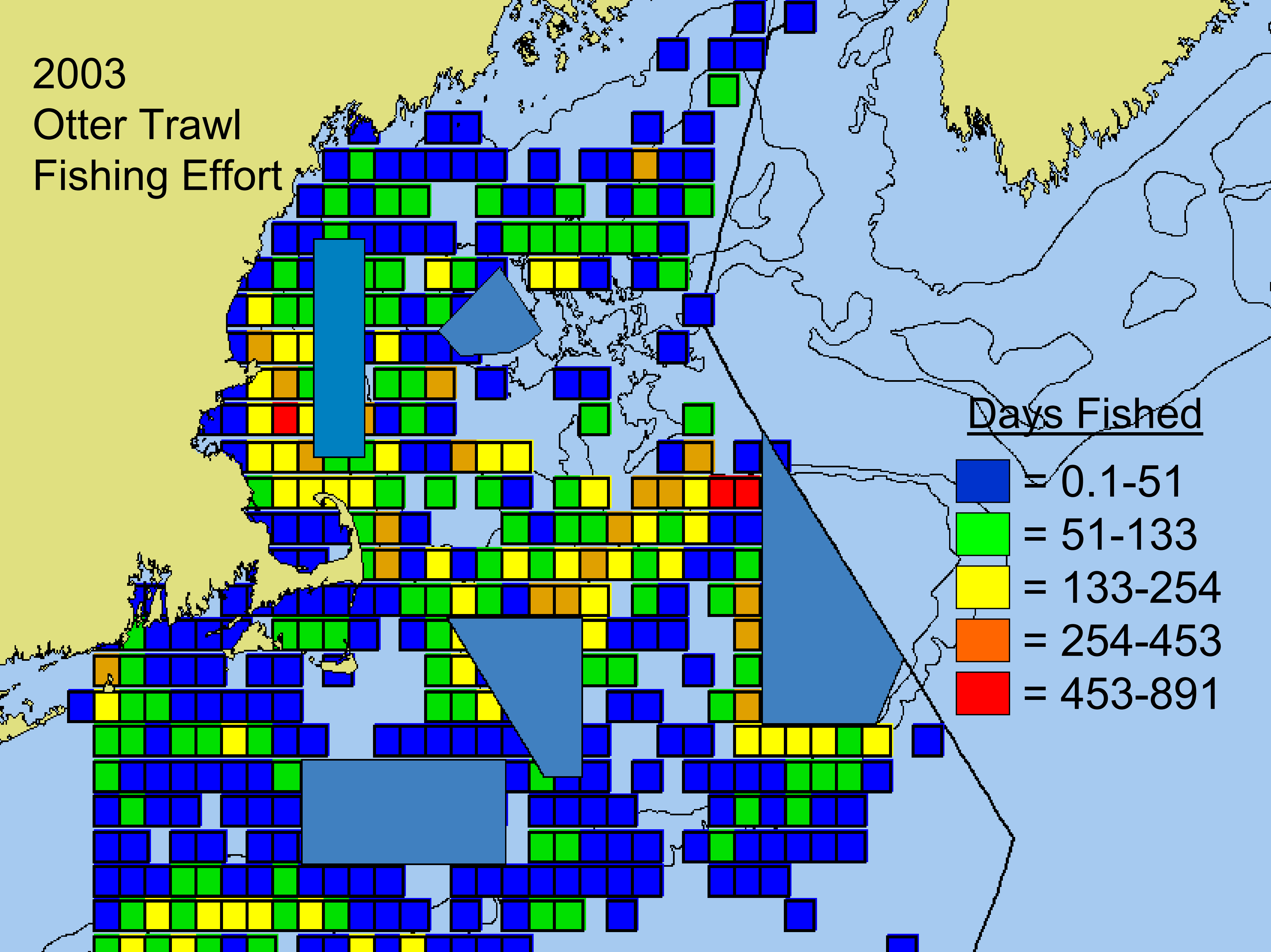
Have groundfish stocks benefited from the Georges Bank closure areas?

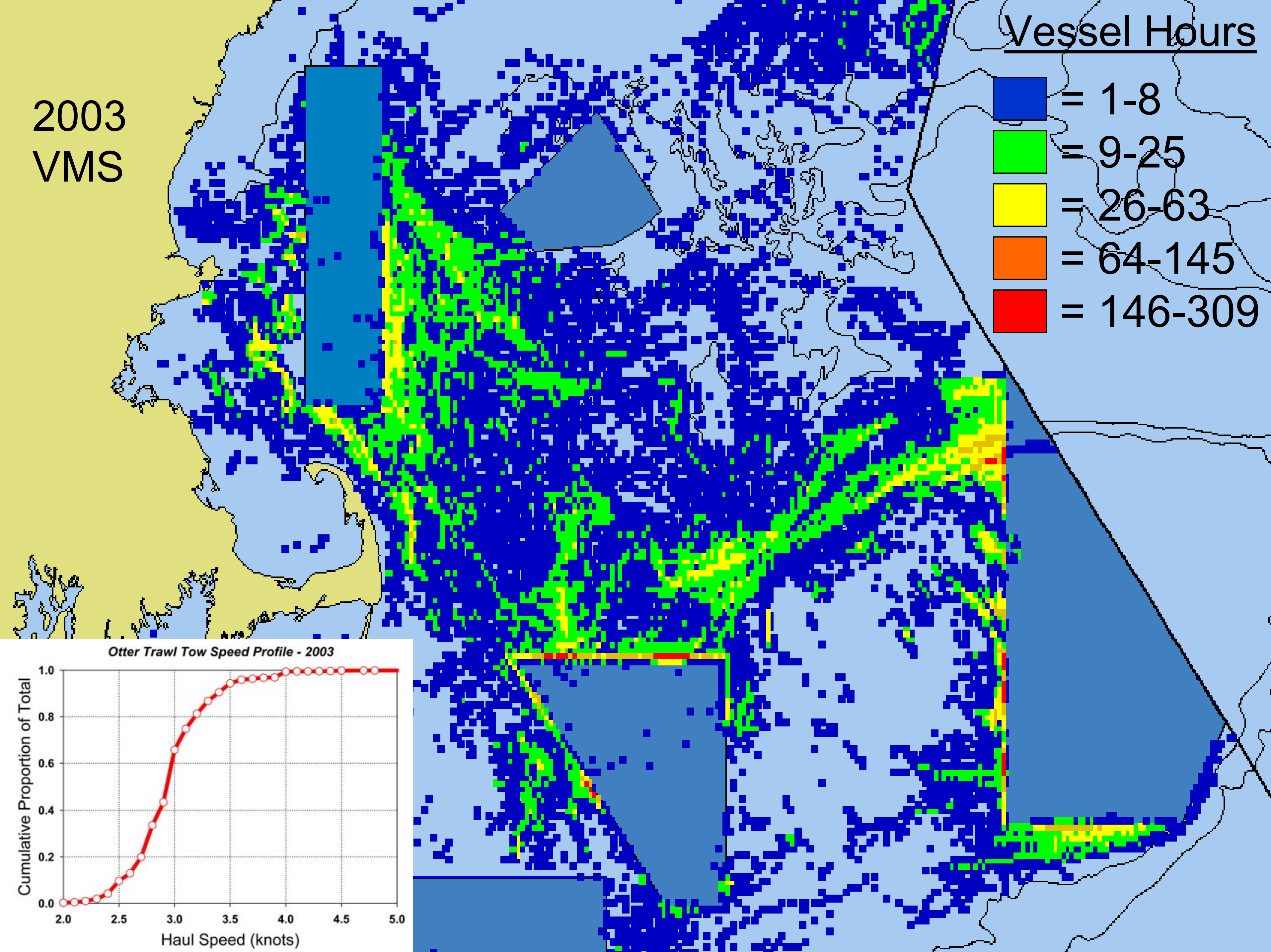
- Mobility of stocks influences
  - Protection afforded by closed area
  - Vulnerability to fleet on the margin
- Comparisons between 2003 VMS and observer data

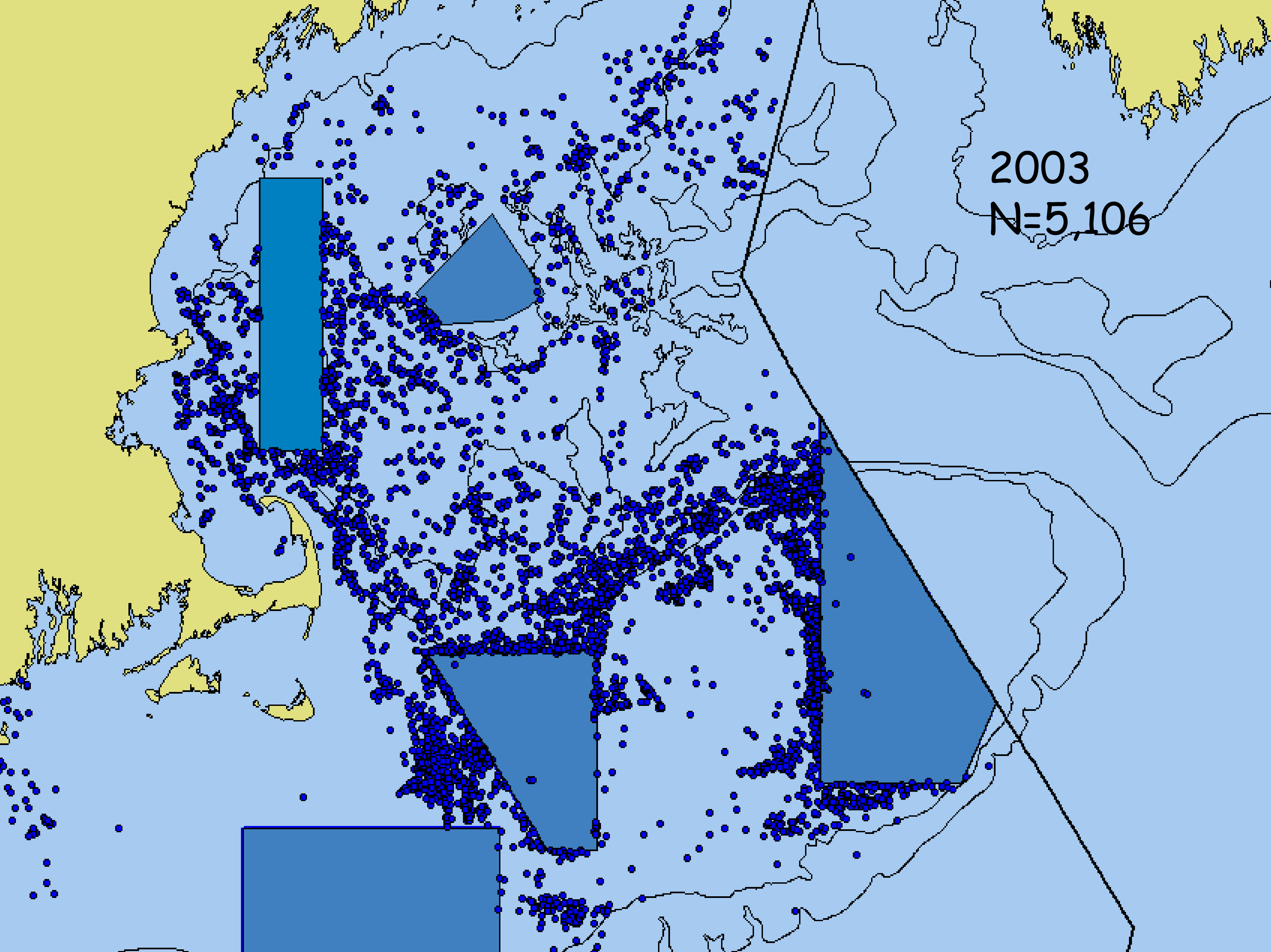


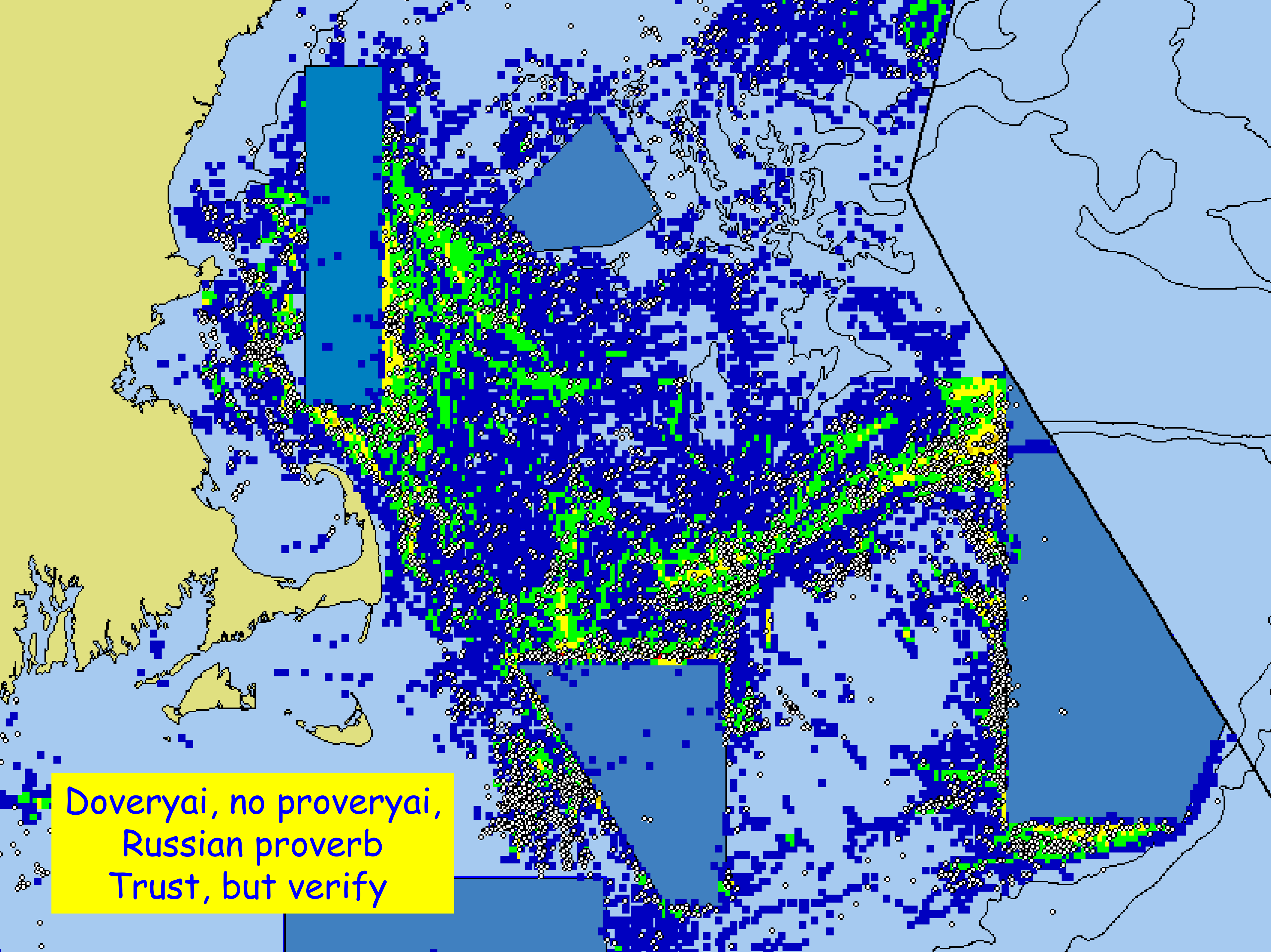
Total Closed Area:
20,187 km²
CA-I = 3,960
CA-II = 6,927
NLS = 6,275
WGOM = 3,025
1996
WGOM
CA-I
CA-II
NLS
Canada
USA
1994:
CA-I
CA-II
NLS
New England
Closed Areas

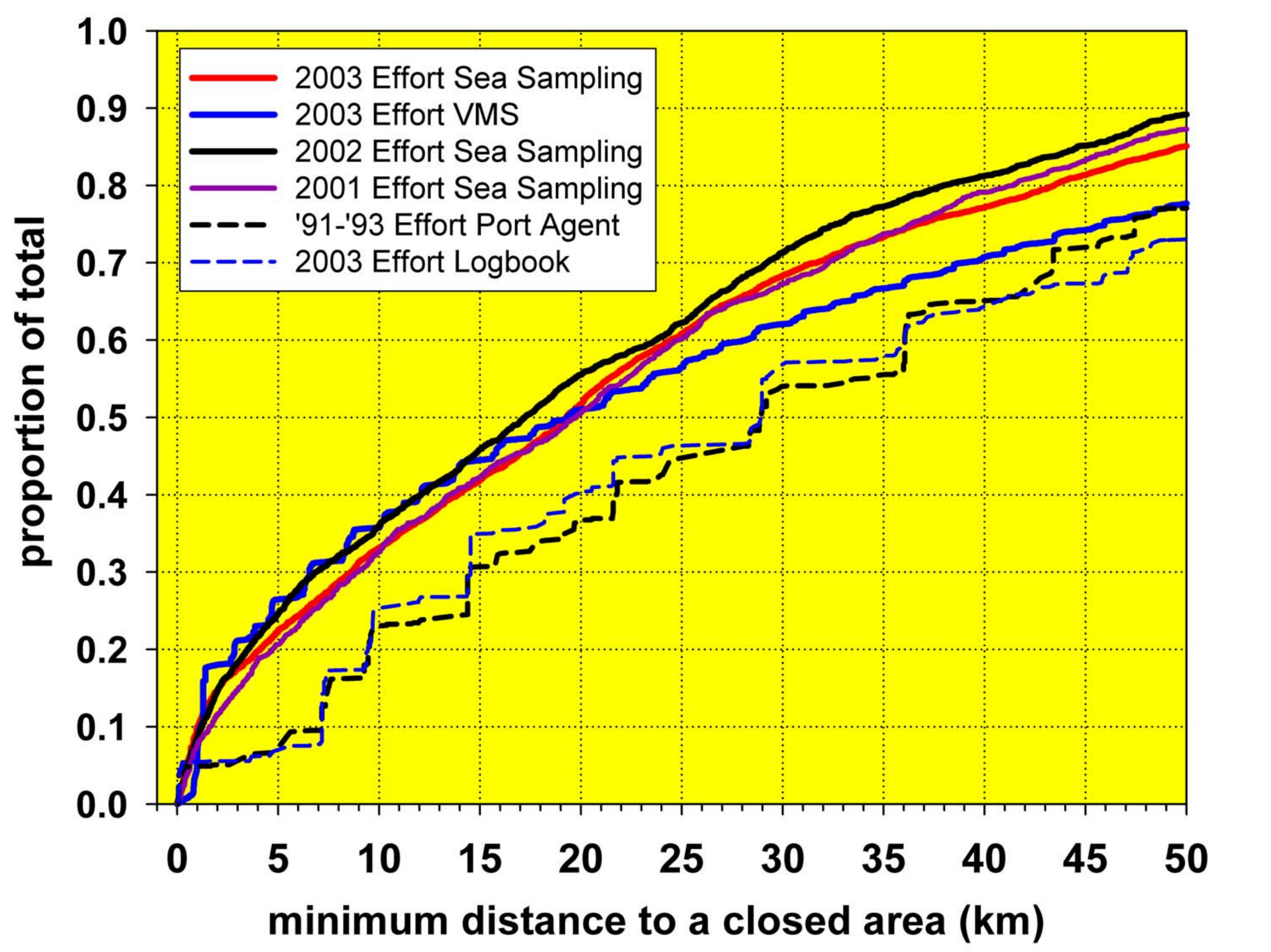

1991-1993
Otter Trawl Effort
Days Fished
= 0.1-177
= 177-571
= 571-1240
= 1240-2244
= 2244-3982


2003
Otter Trawl
Fishing Effort
Days Fished
= 0.1-51
= 51-133
= 133-254
= 254-453
= 453-891

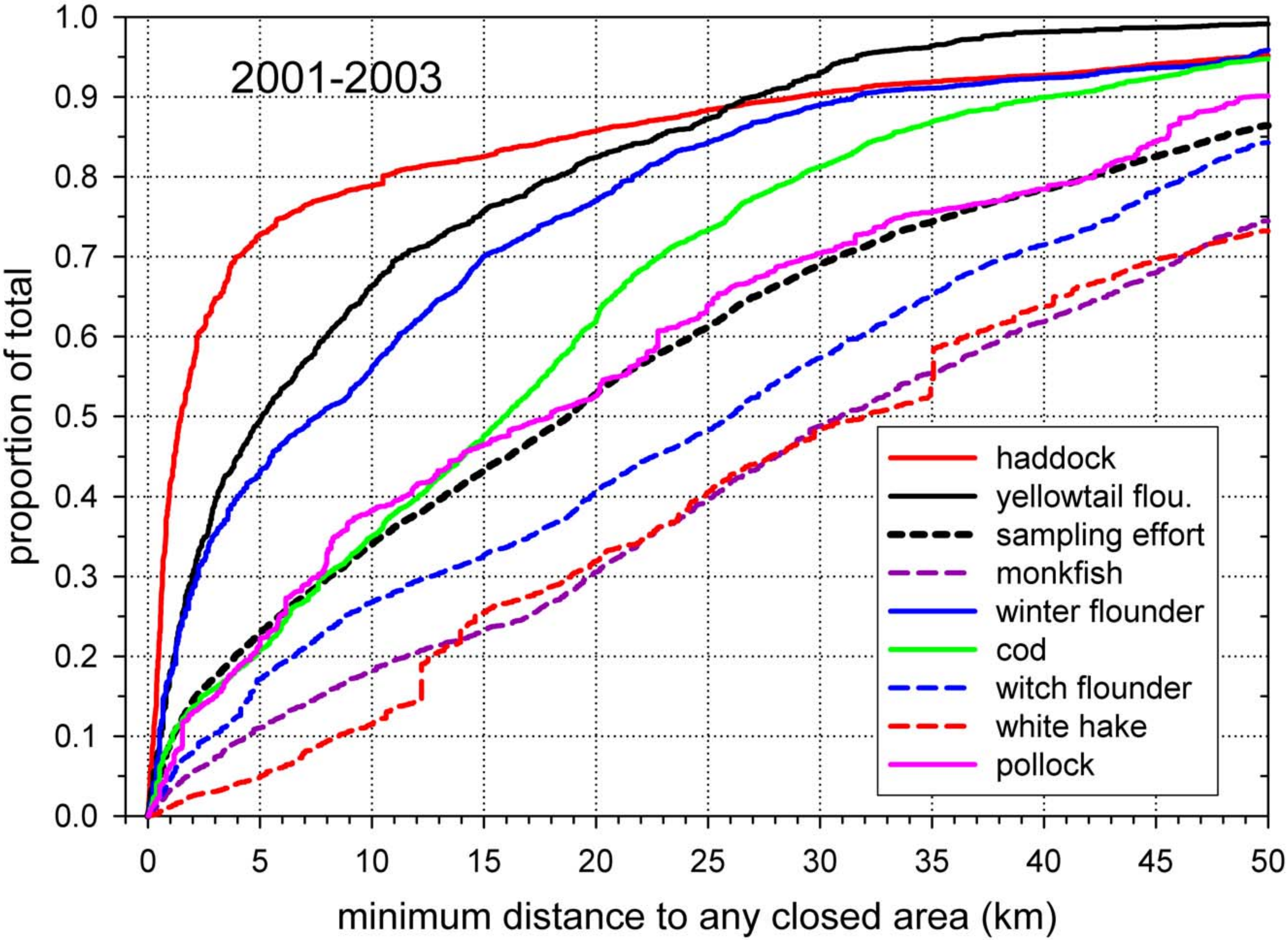

2003
VMS
Vessel Hours
= 1-8
= 9-25
= 26-63
= 64-145
= 146-309
Otter Trawl Tow Speed Profile - 2003
Cumulative Proportion of Total
Haul Speed (knots)
0.0
0.2
0.4
0.6
0.8
1.0
2.0
2.5
3.0
3.5
4.0
4.5
5.0


2003
N=5,106

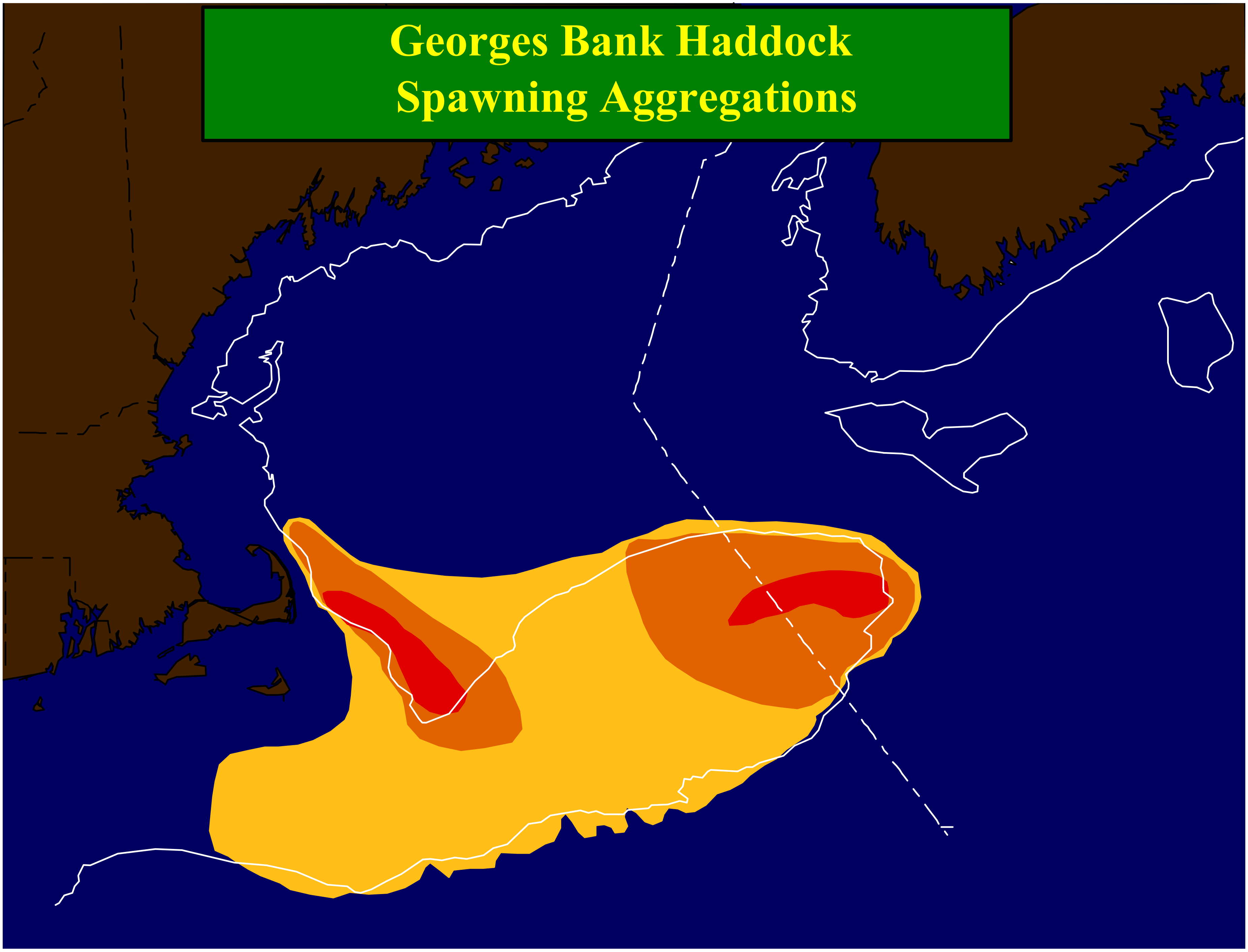

Doveryai, no proveryai,
Russian proverb
Trust, but verify

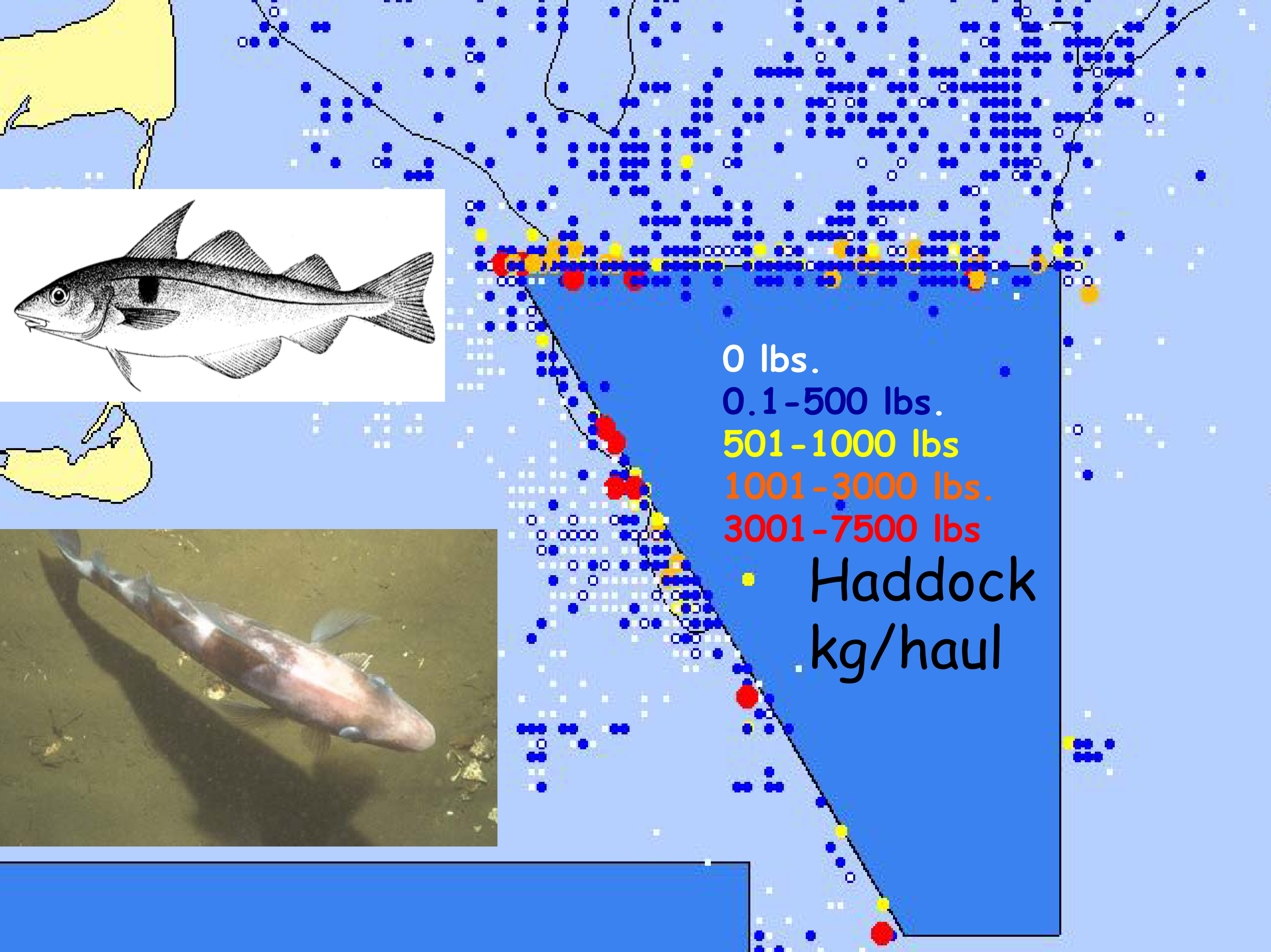


2003 Effort Sea Sampling
2003 Effort VMS
2002 Effort Sea Sampling
2001 Effort Sea Sampling
'91-'93 Effort Port Agent
2003 Effort Logbook
proportion of total
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
0
5
10
15
20
25
30
35
40
45
50
minimum distance to a closed area (km)



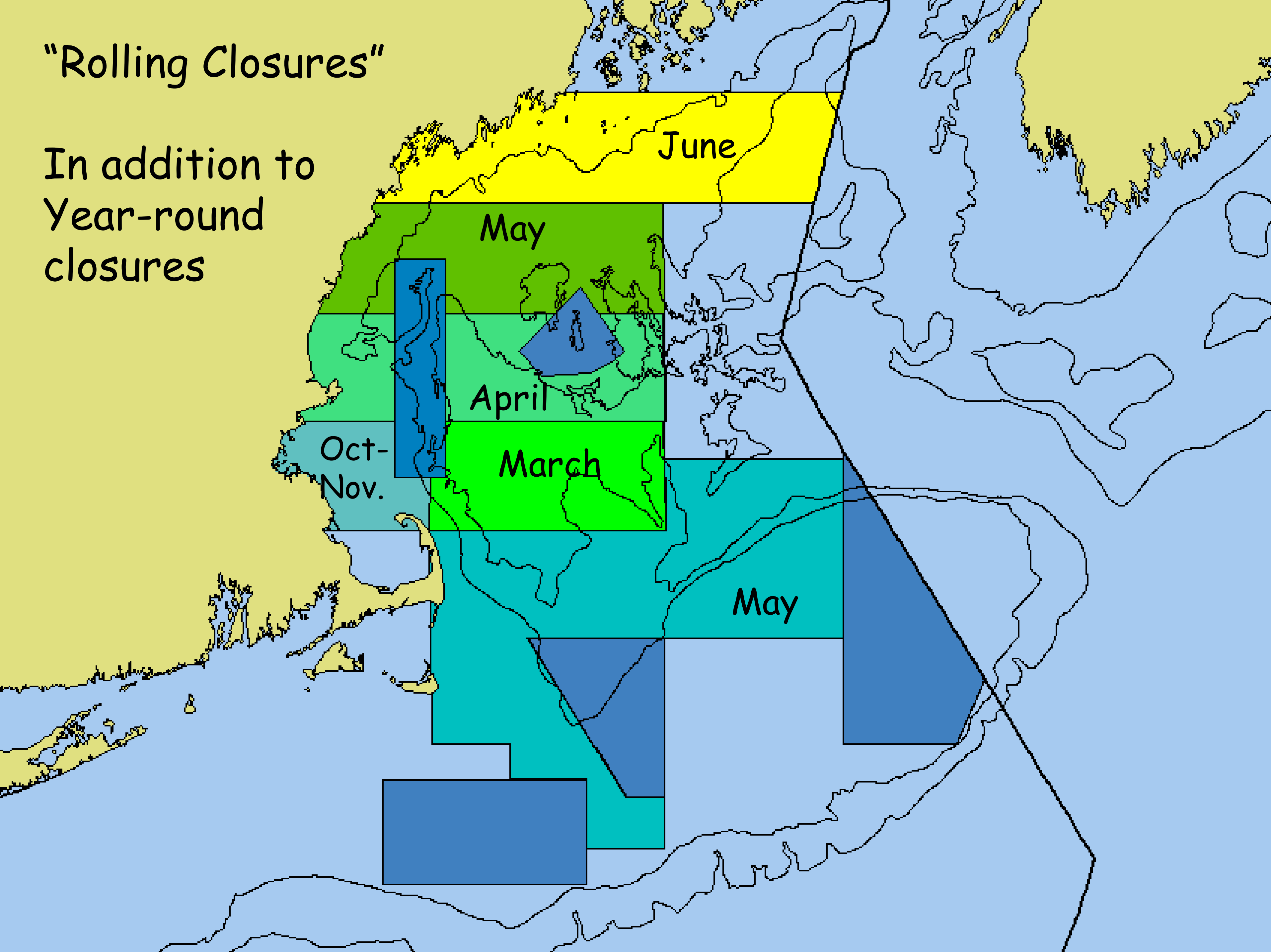
2001-2003
proportion of total
minimum distance to any closed area (km)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
0
5
10
15
20
25
30
35
40
45
50
haddock
yellowtail flou.
sampling effort
monkfish
winter flounder
cod
witch flounder
white hake
pollock

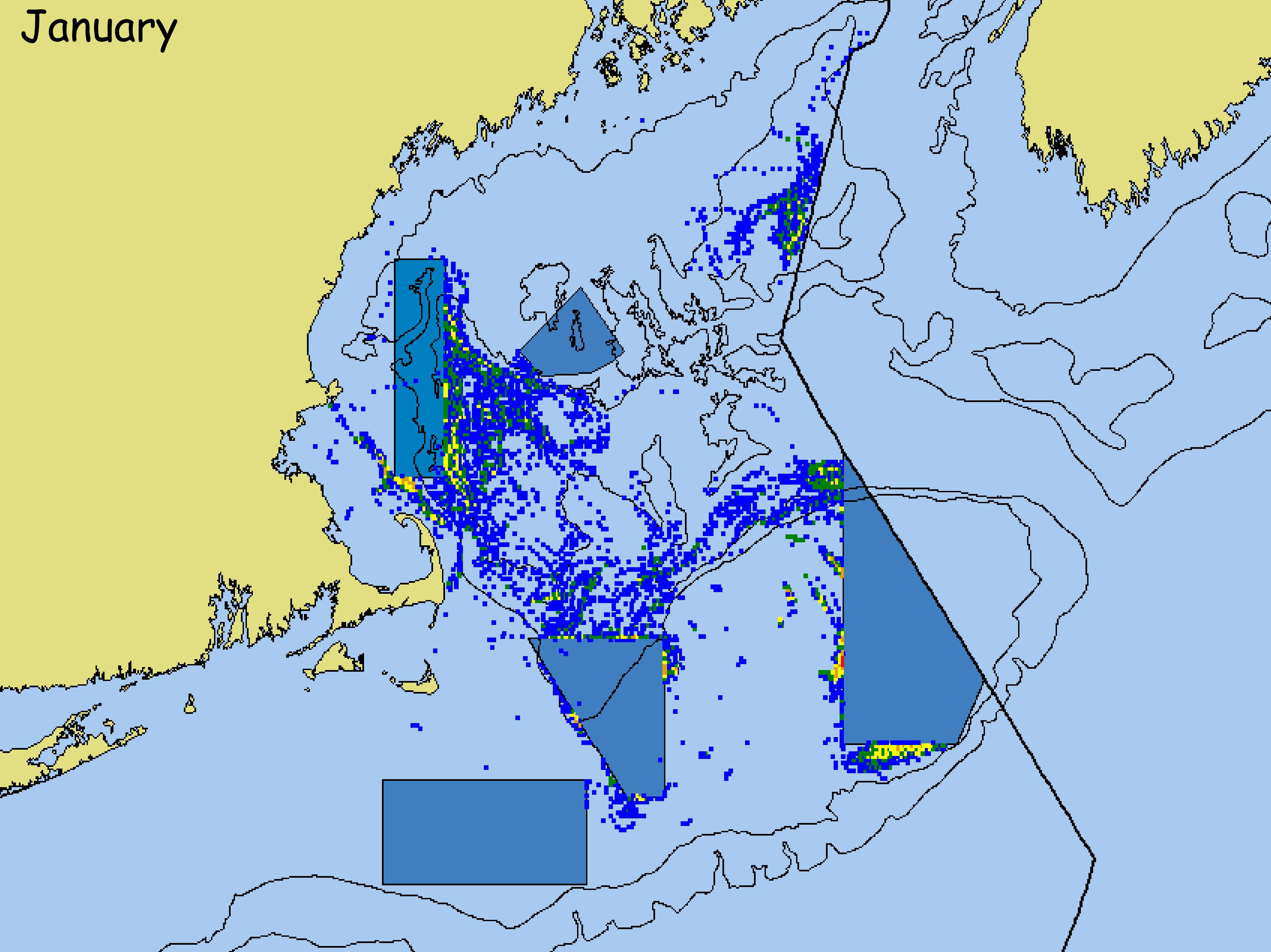

Georges Bank Haddock
Spawning Aggregations

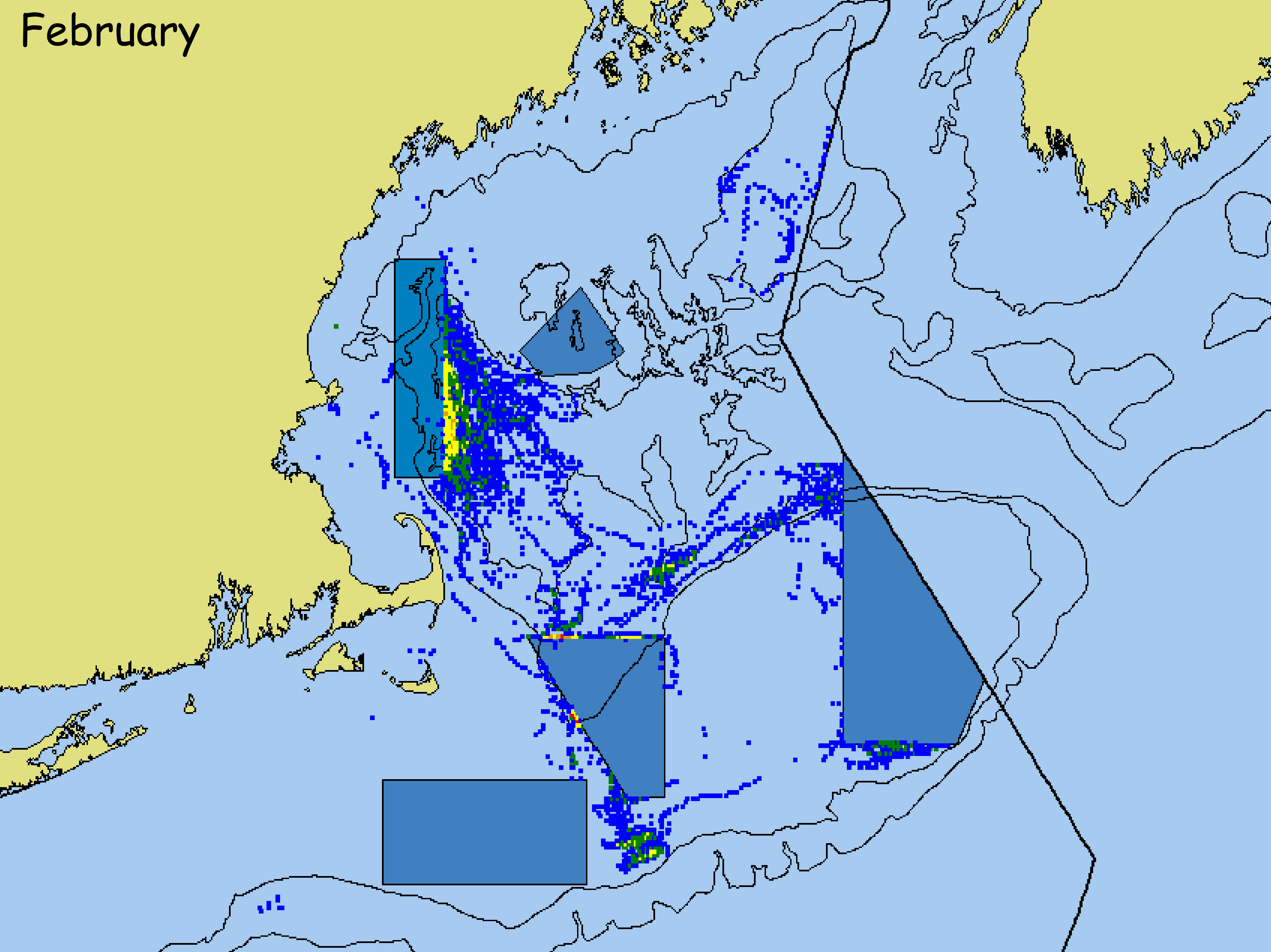

0 lbs.
0.1-500 lbs.
501-1000 lbs
1001-3000 lbs.
3001-7500 lbs
Haddock
kg/haul

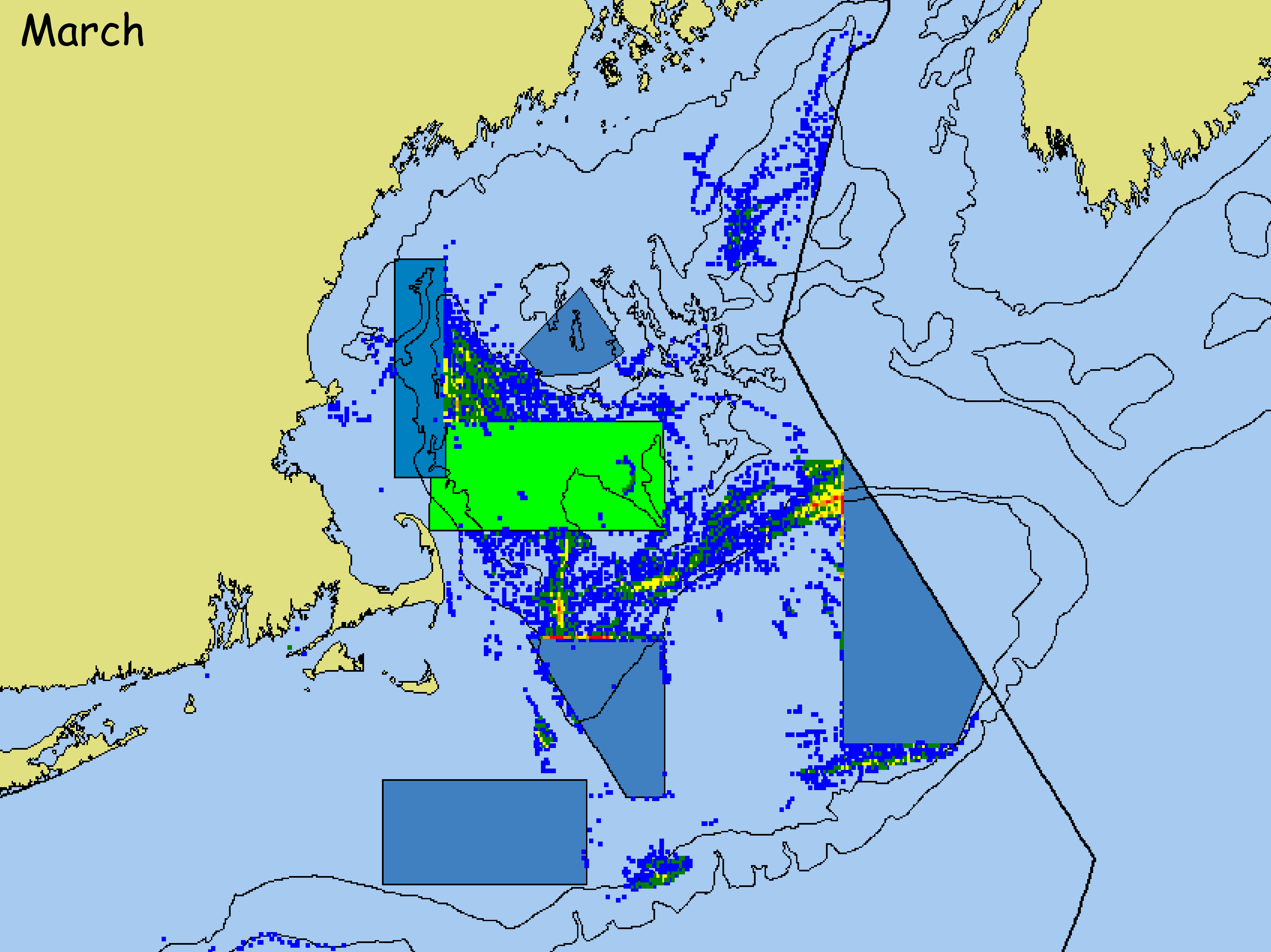
“Rolling Closures”

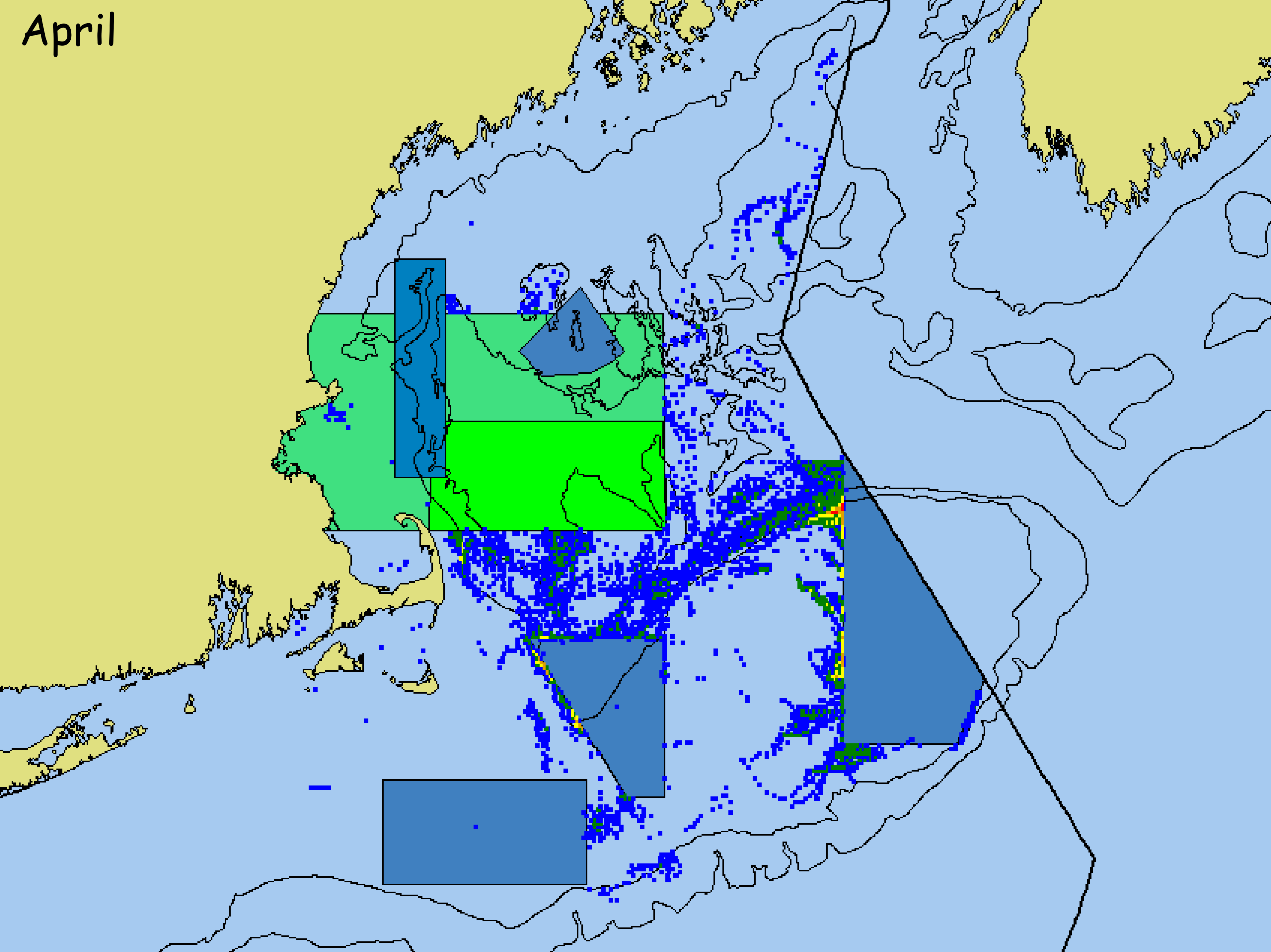
In addition to Year-round closures

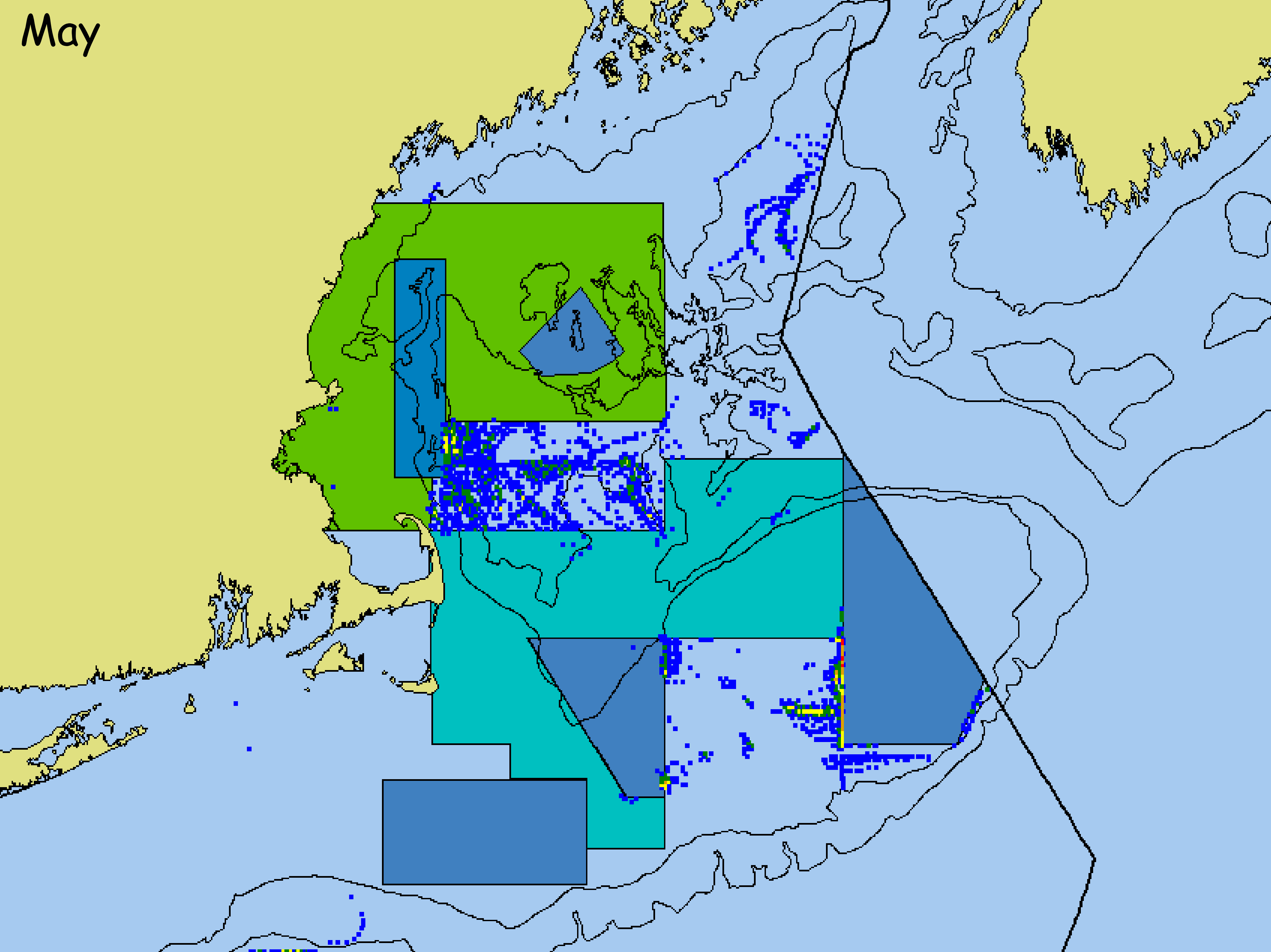


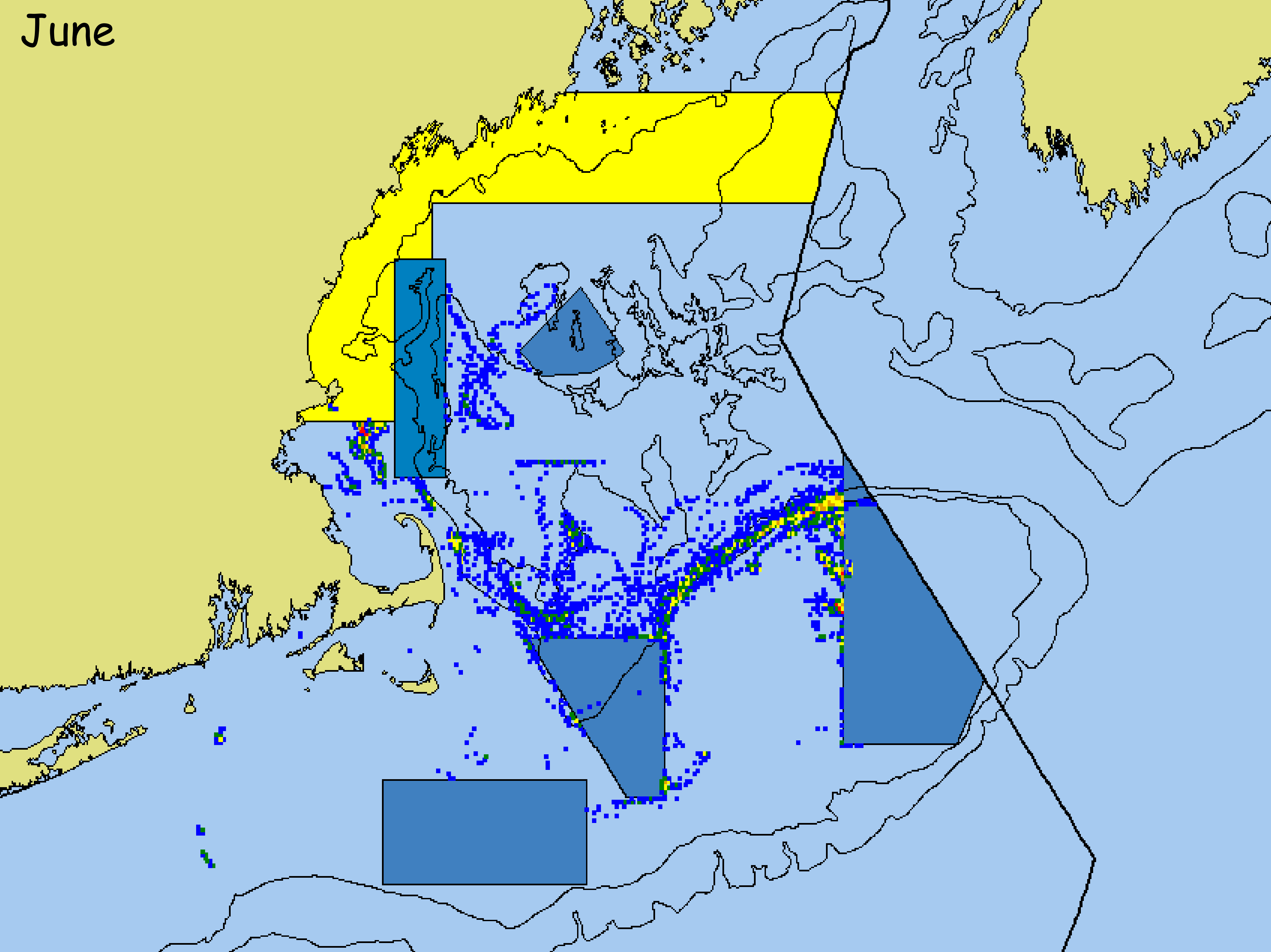

January

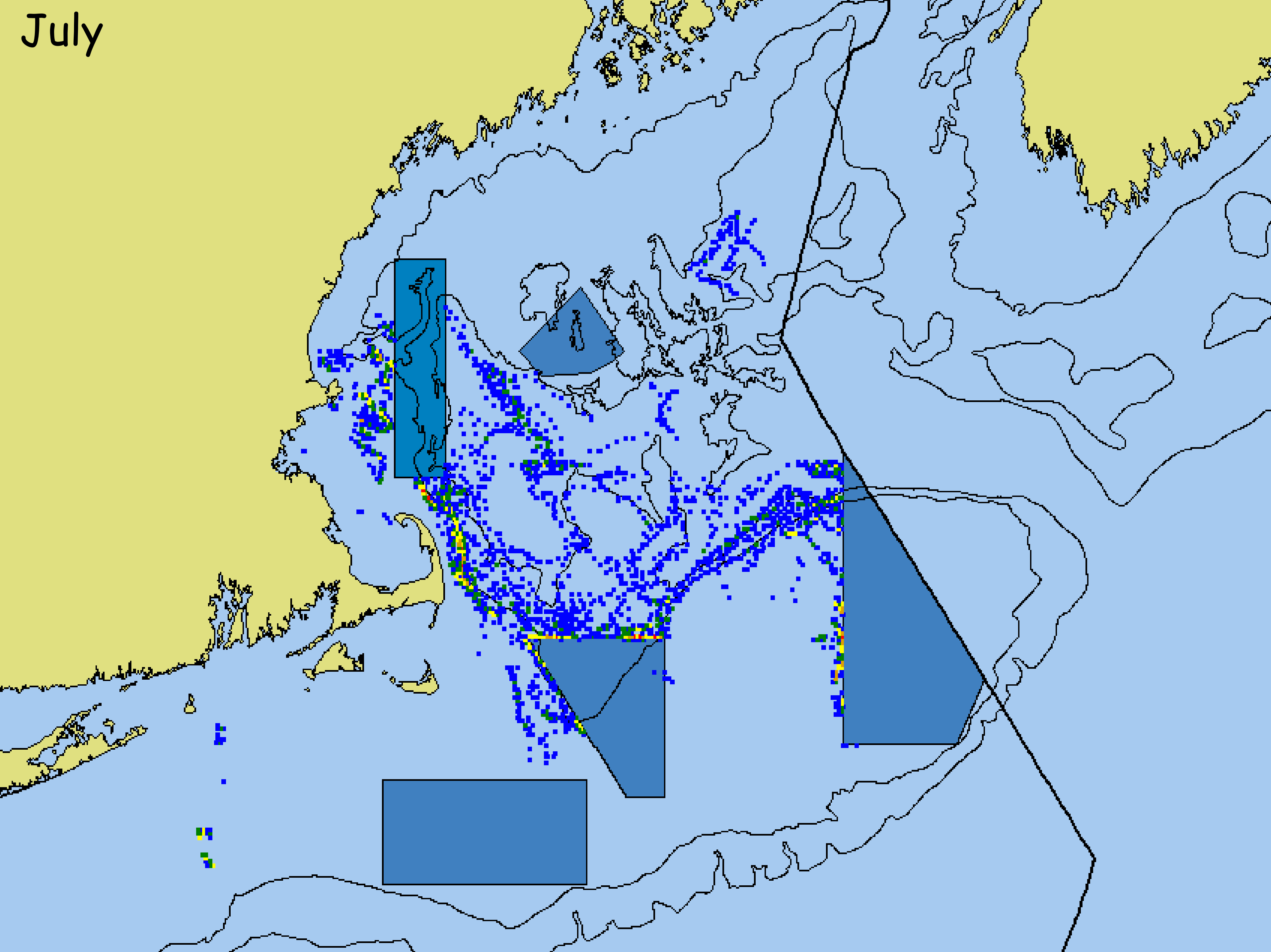

February

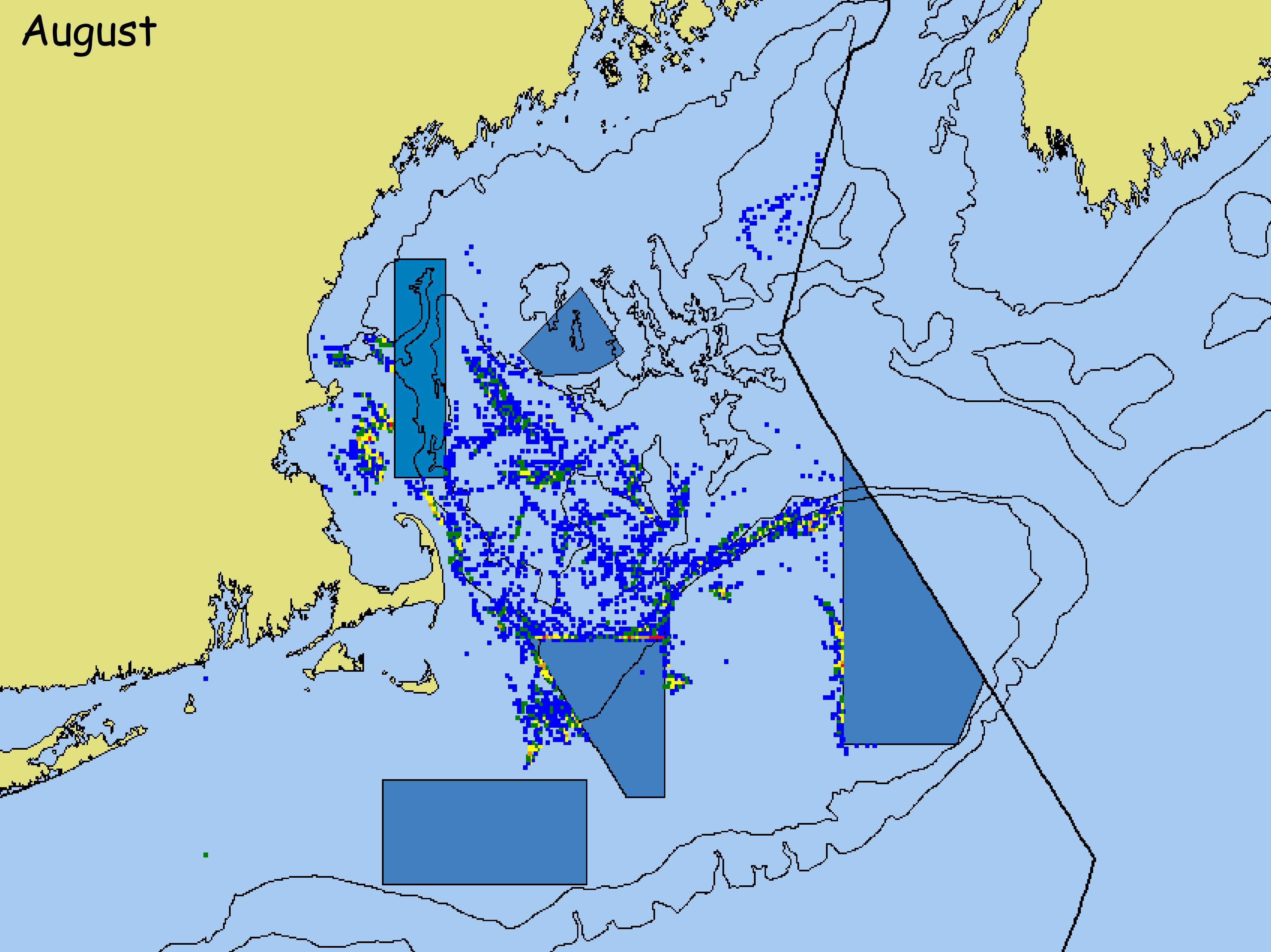

March

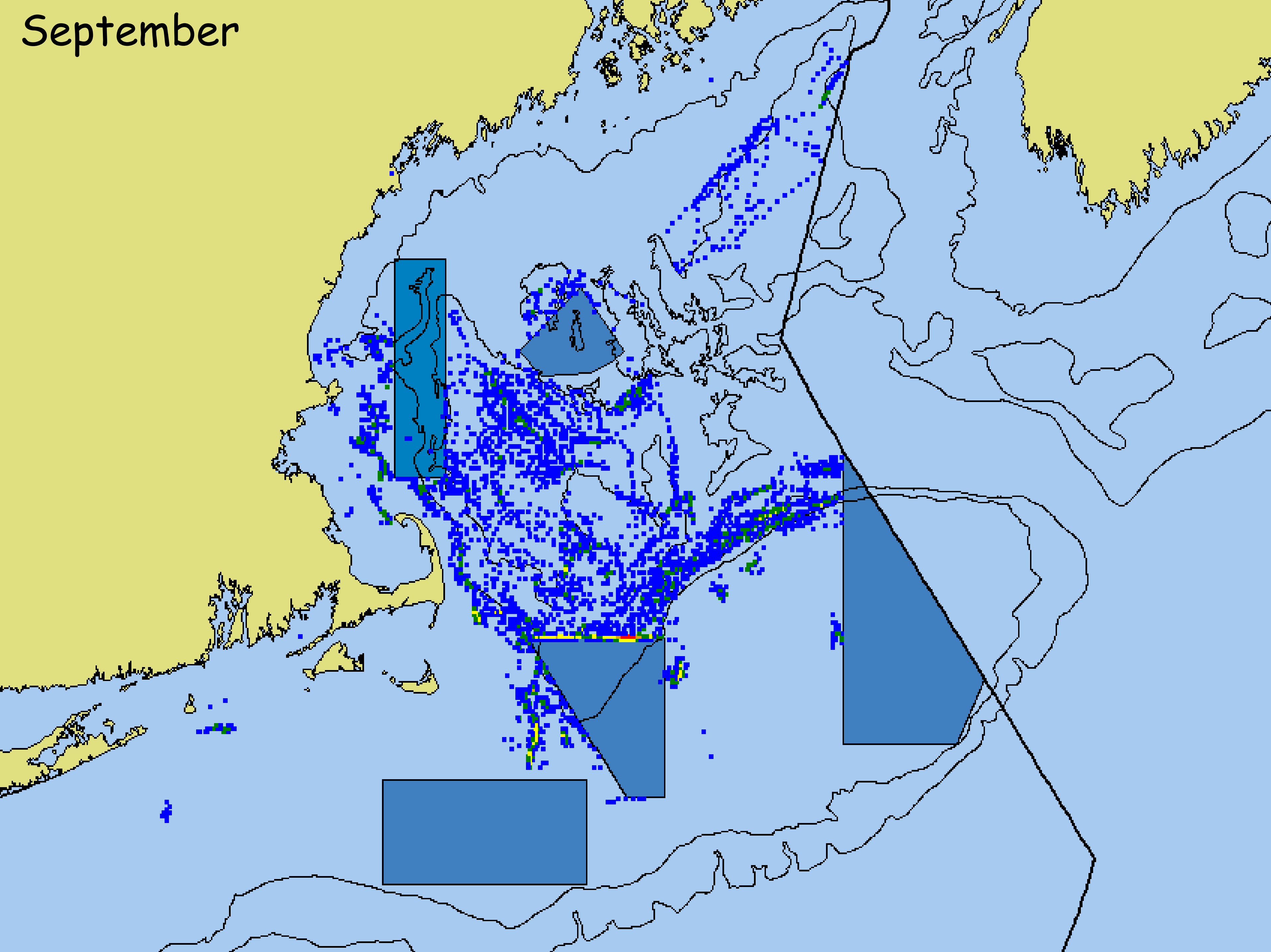

April

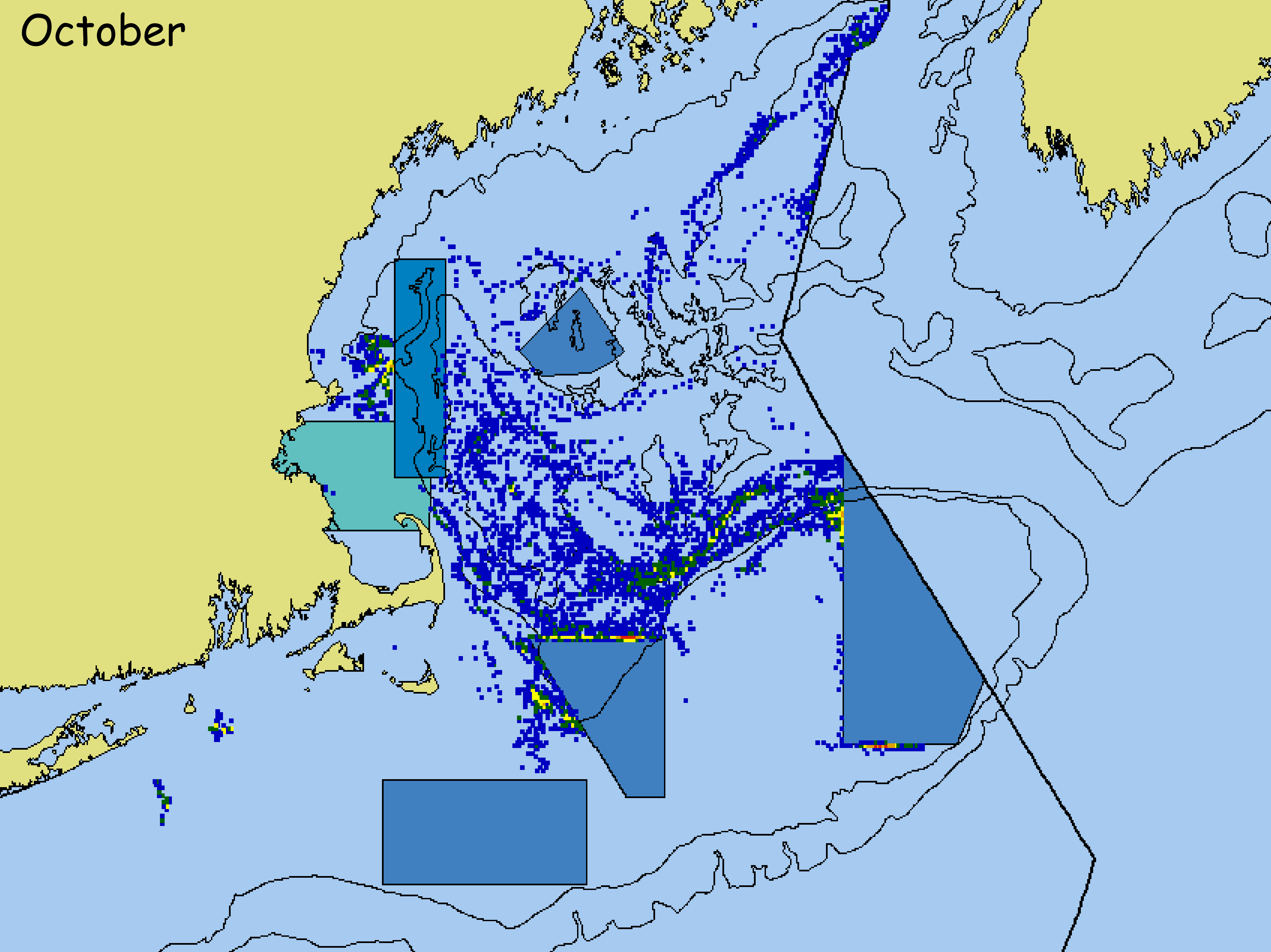

May


June

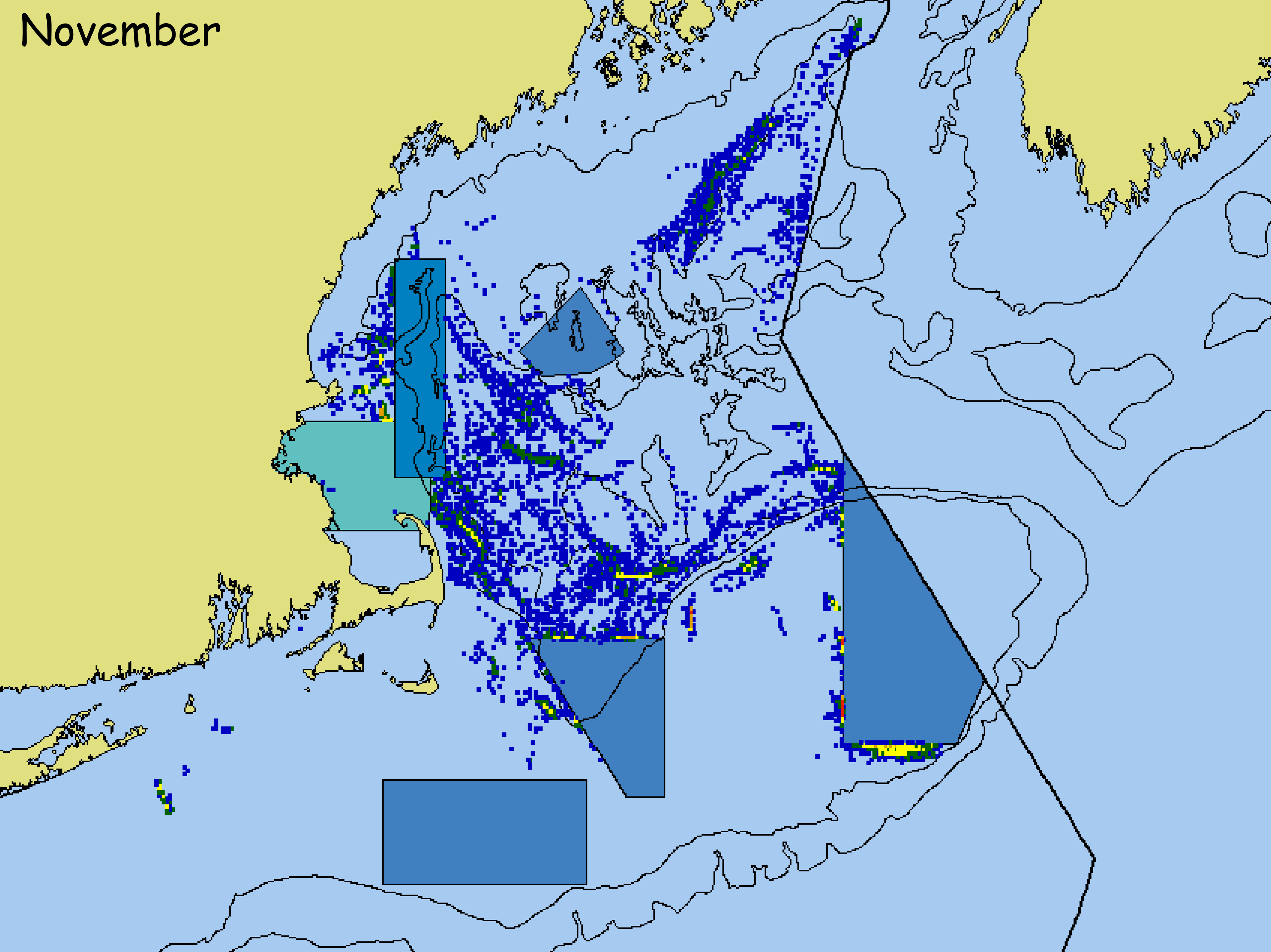

July

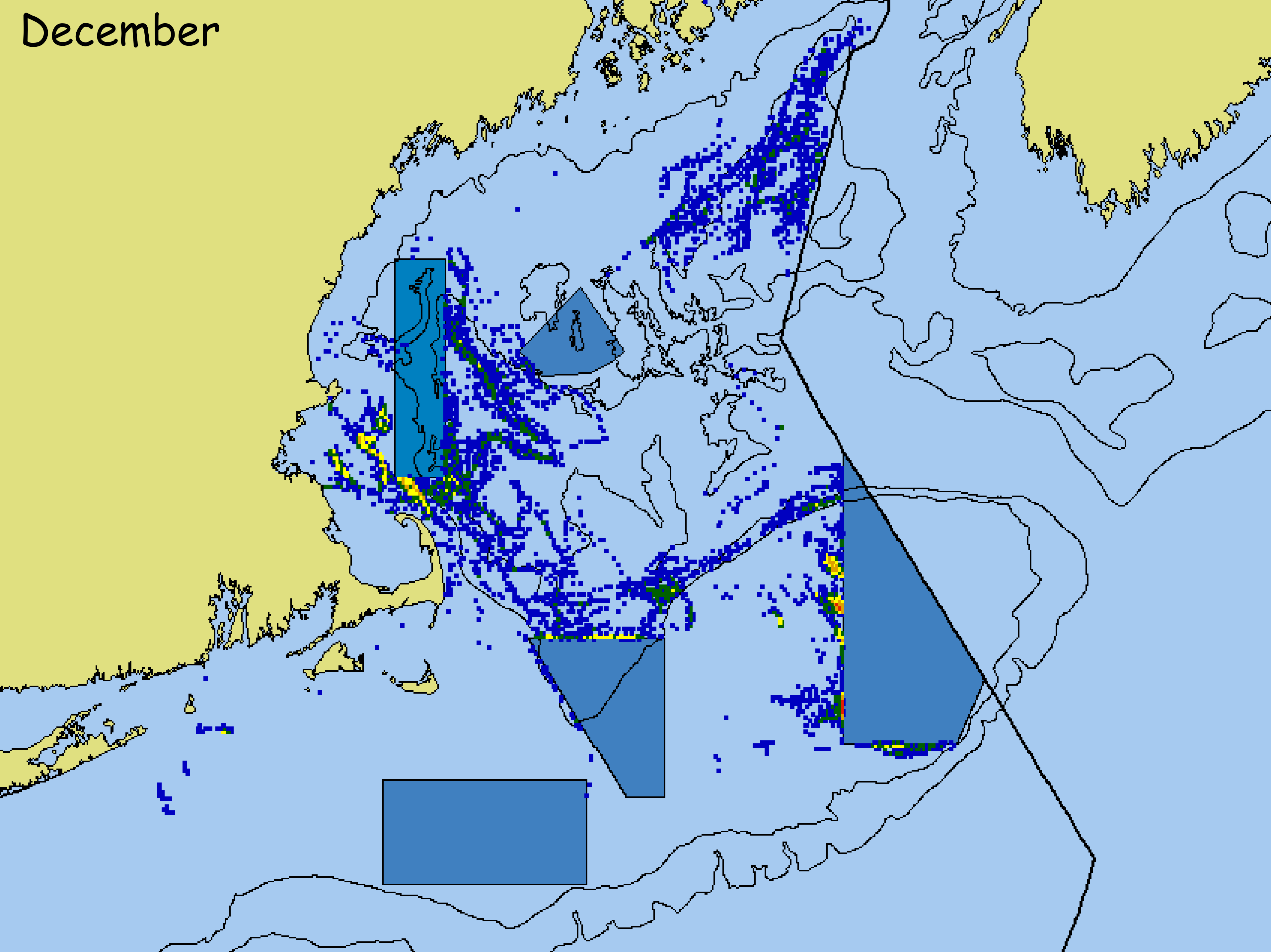

August


September


October

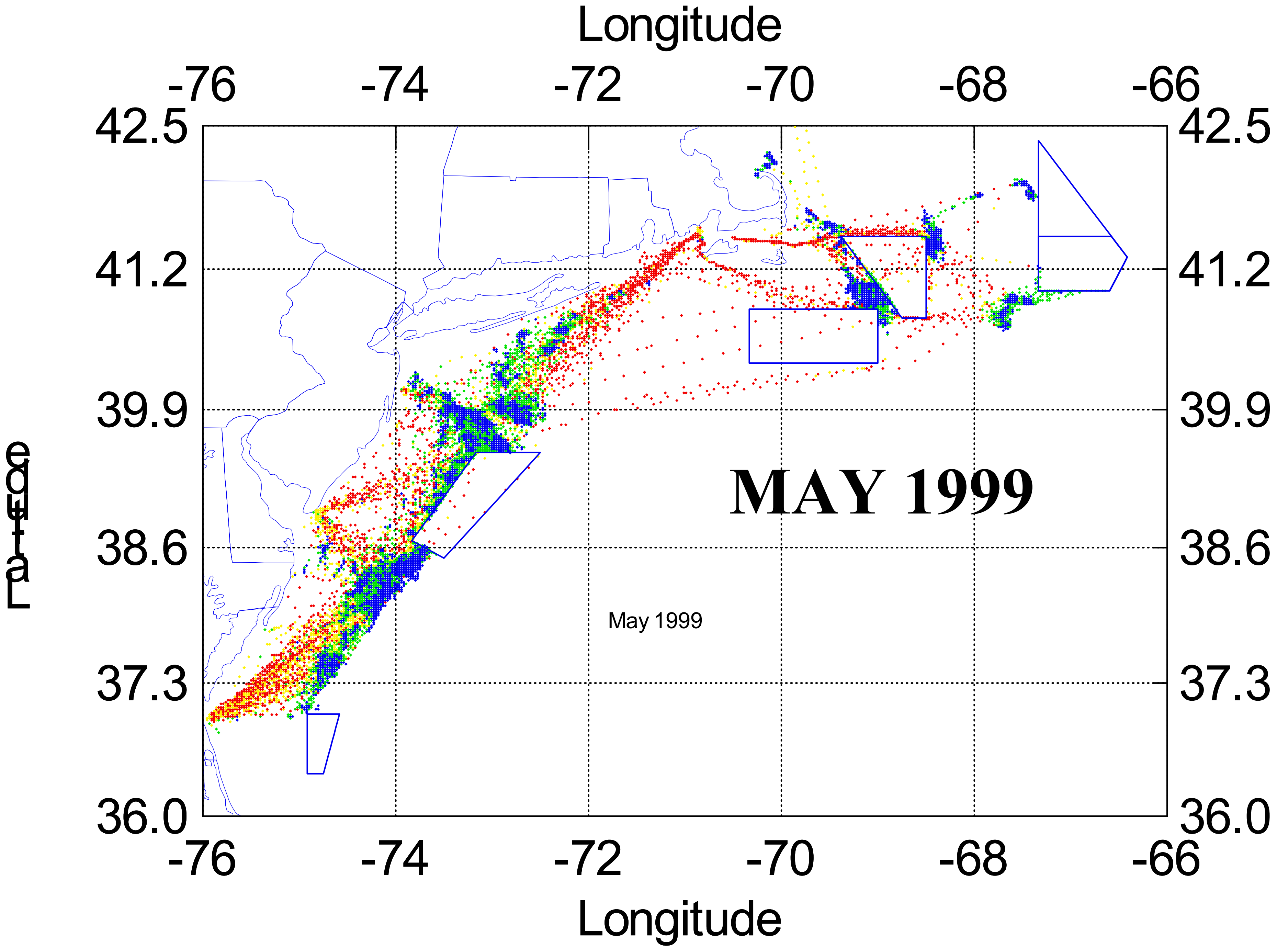
November



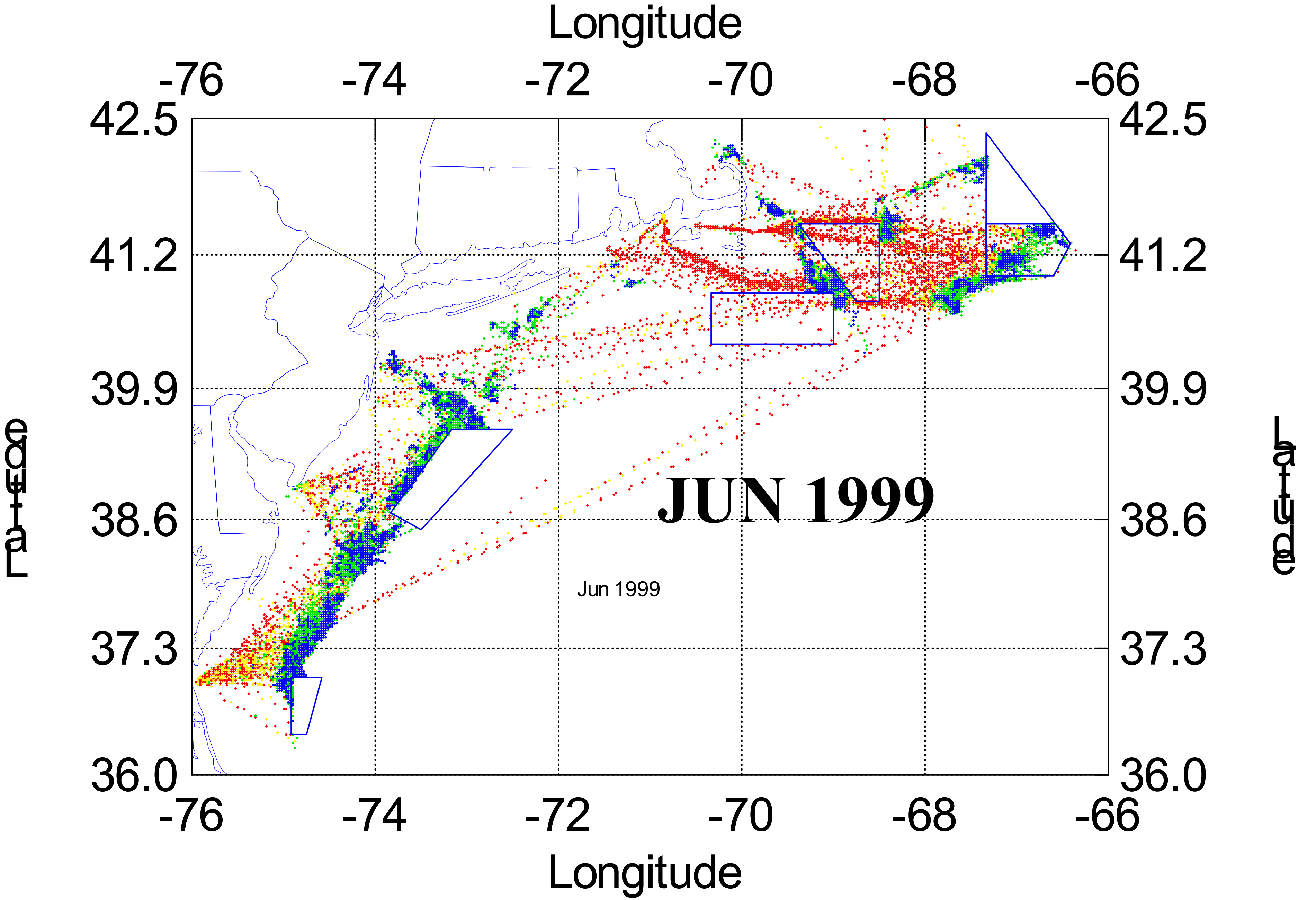

December

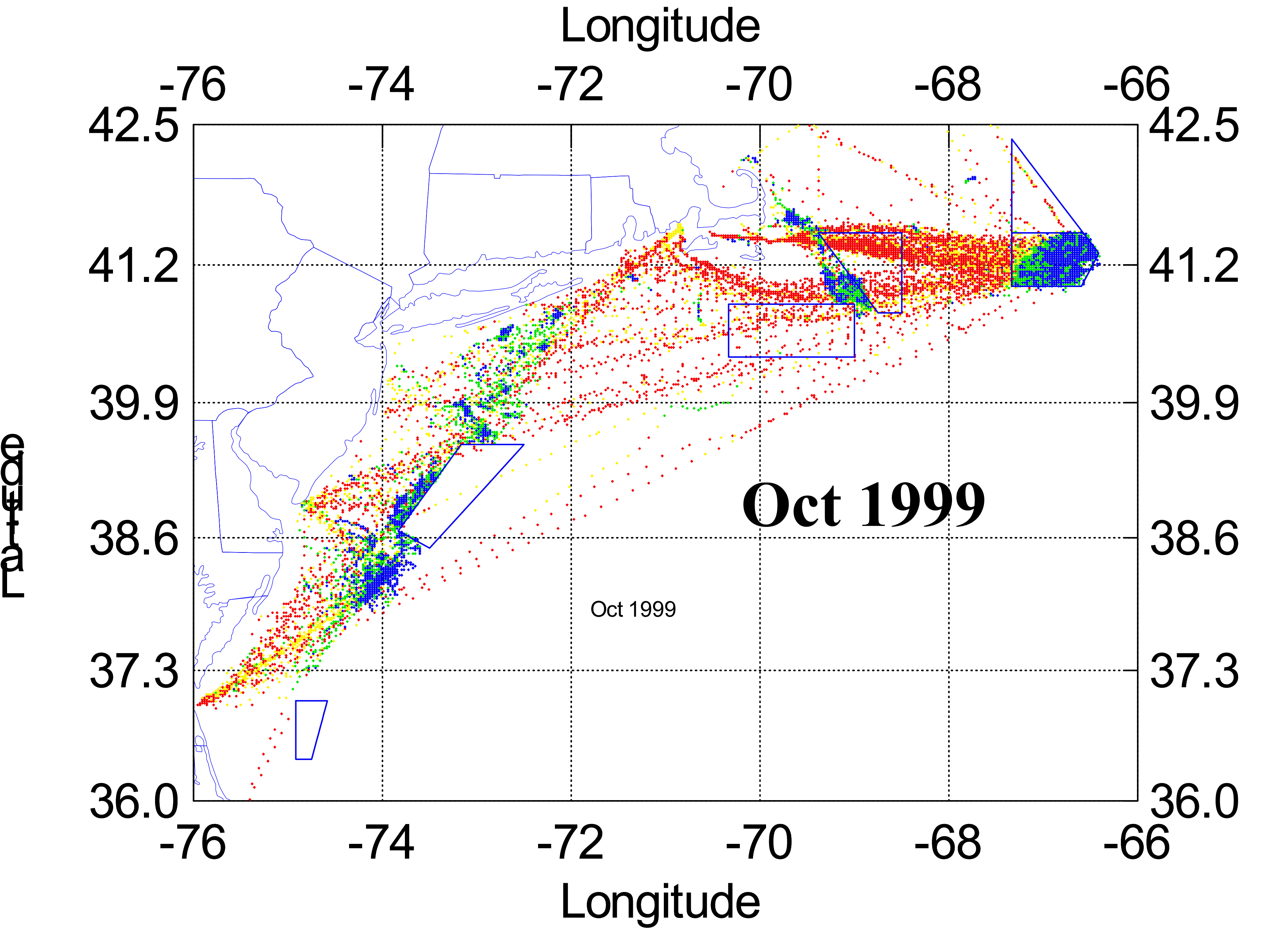
Velocity Plots: Scallop Fishery

- The next series of plots illustrate the average velocity for vessels in 1 nm squares
- These plots emphasize the primary fishing areas in blue and green and the major ports and routes of fishing vessels
- Red 7.5- 10 knots
- Yellow 5.0-7.5 knots
- Green 2.5-5.0 knots
- Blue 0. -2.5 knots



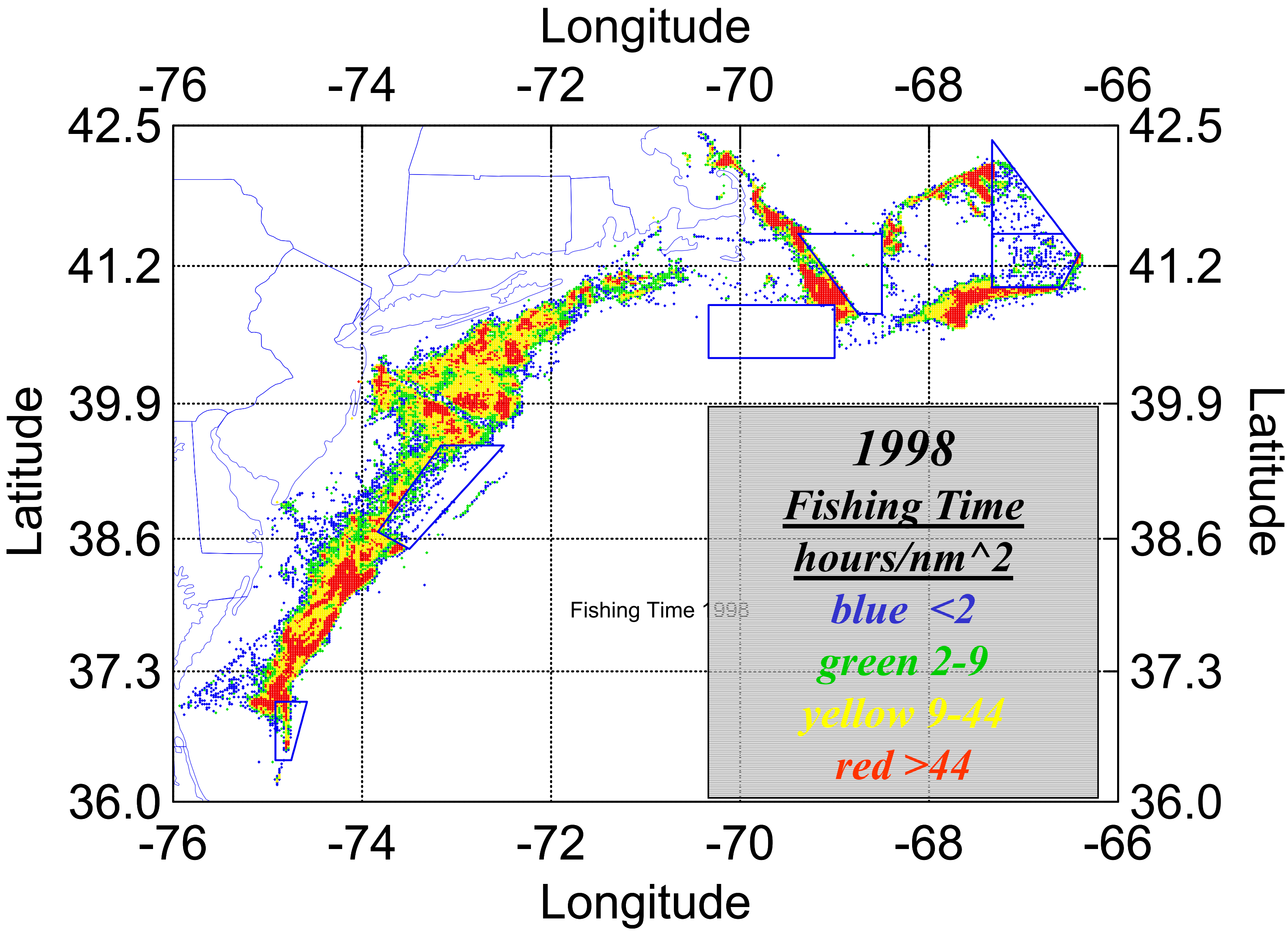
Longitude
-76
-74
-72
-70
-68
-66
42.5
41.2
39.9
38.6
37.3
36.0
Latitude
MAY 1999
May 1999


Longitude
-76
-74
-72
-70
-68
-66
42.5
41.2
39.9
38.6
37.3
36.0
Latitude
JUN 1999
Jun 1999

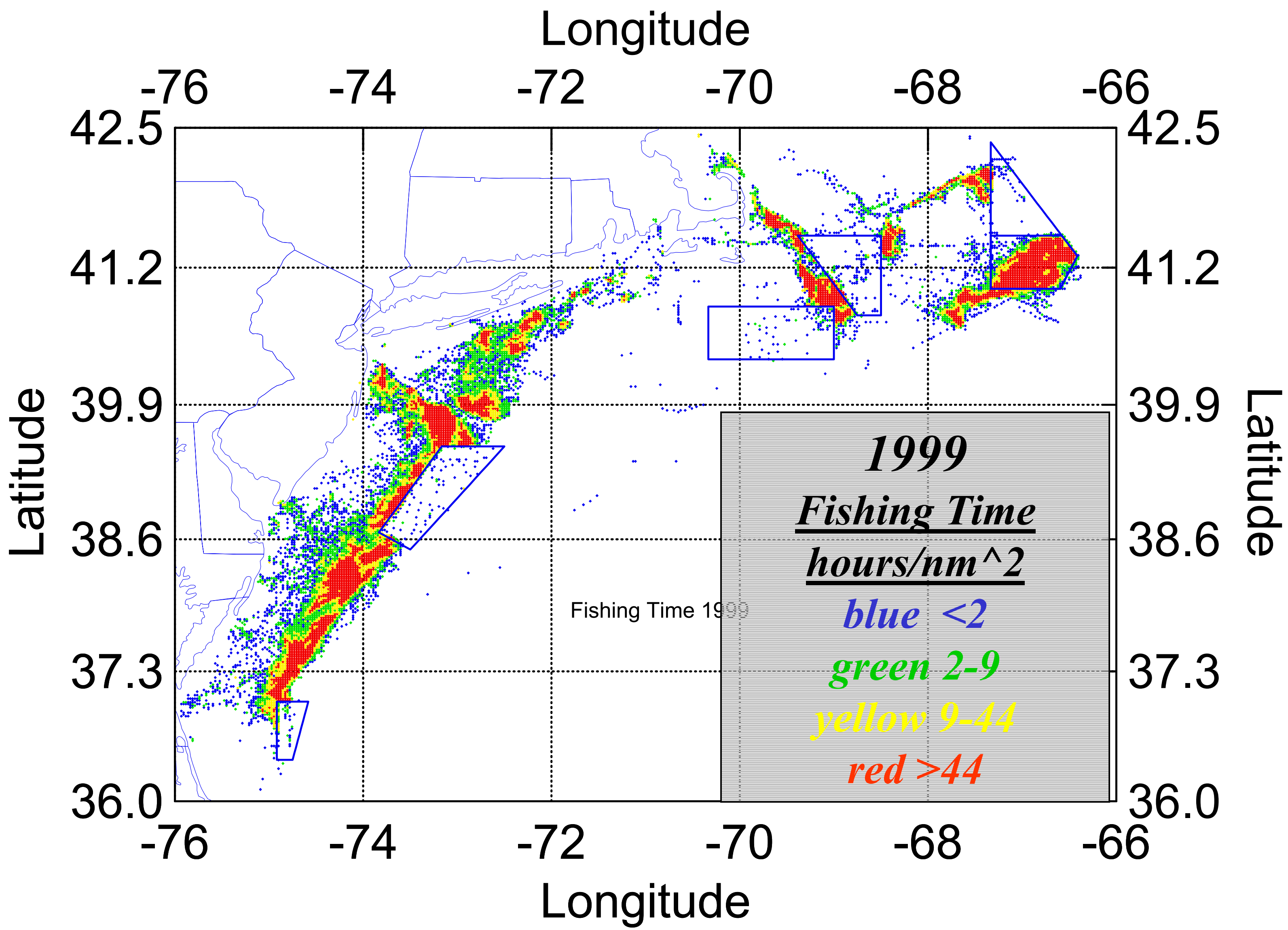

Longitude
-76
-74
-72
-70
-68
-66
42.5
41.2
39.9
38.6
37.3
36.0
Oct 1999
Oct 1999
Longitude

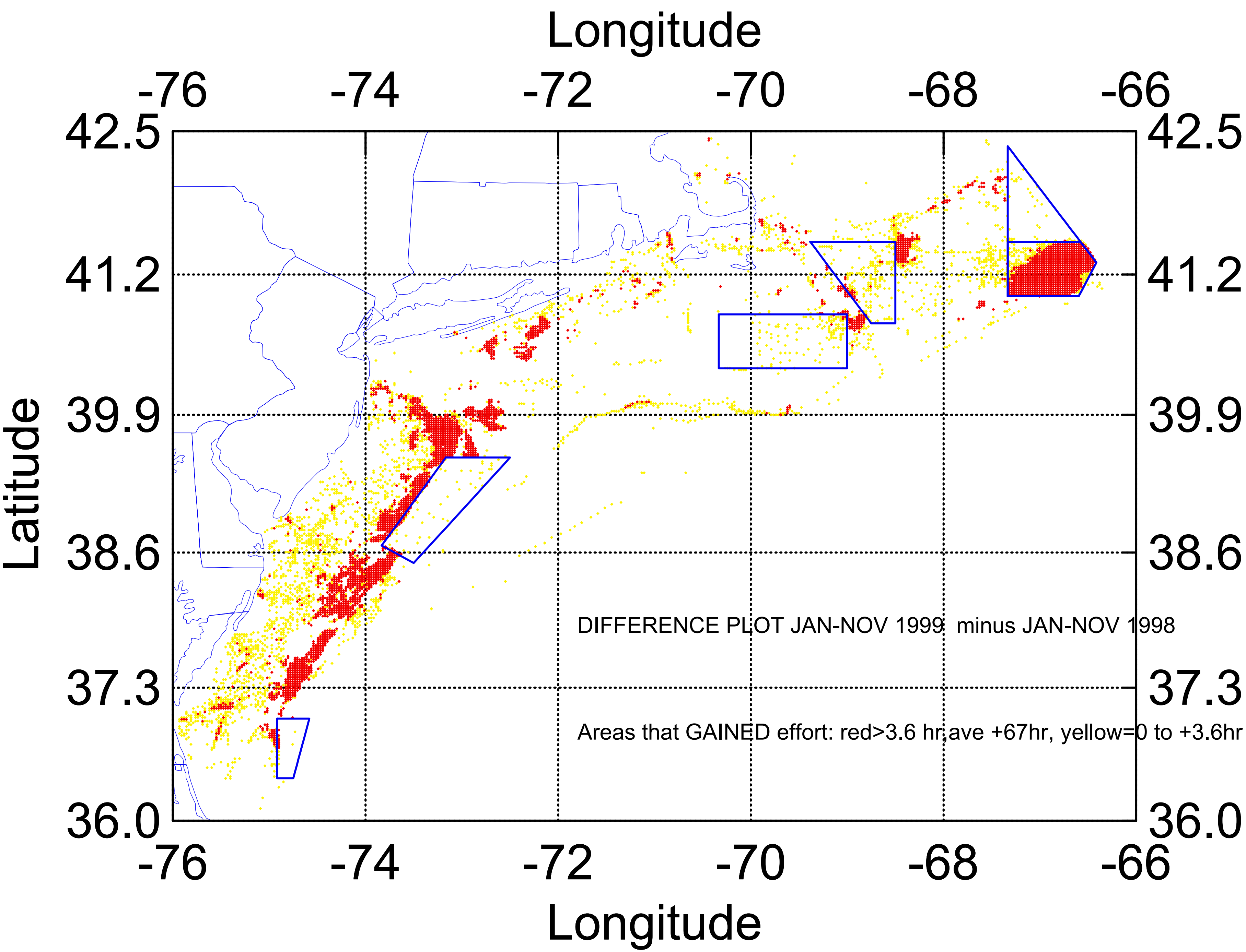
Composite and Difference Plots, 1998-1999

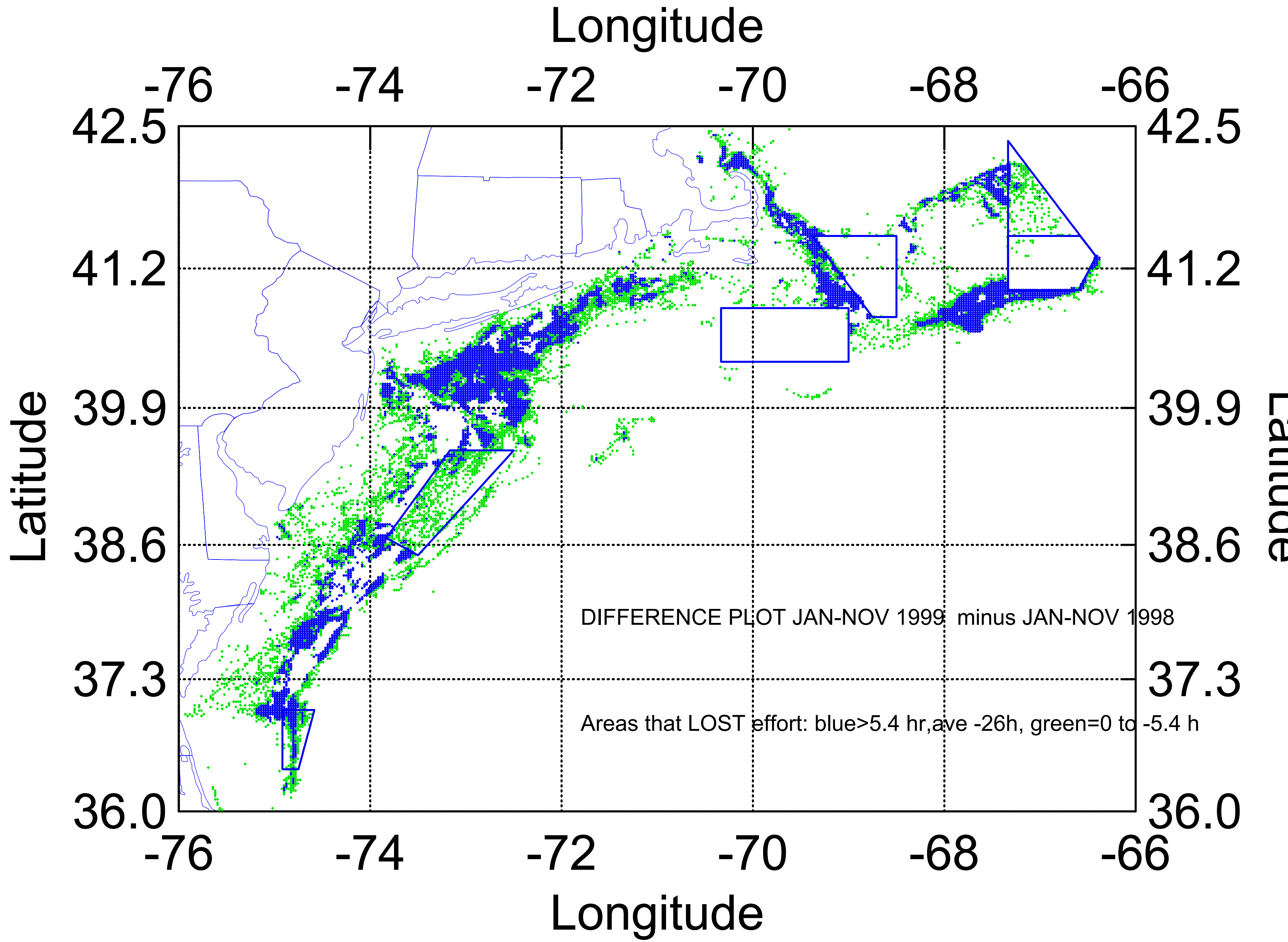
- Next 3 plots represent comparison of overall pattern of fishing effort (hours fished) for the 1998 and 1999 fishing years.
- Difference plot is based on subtraction of total hours fished by cell in 1998 from hours fished in 1999 in that same cell.



Longitude
-76
-74
-72
-70
-68
-66
42.5
41.2
39.9
38.6
37.3
36.0
Latitude
Latitude
1998
Fishing Time
hours/nm^2
blue <2
green 2-9
yellow 9-44
red >44
Fishing Time 1998

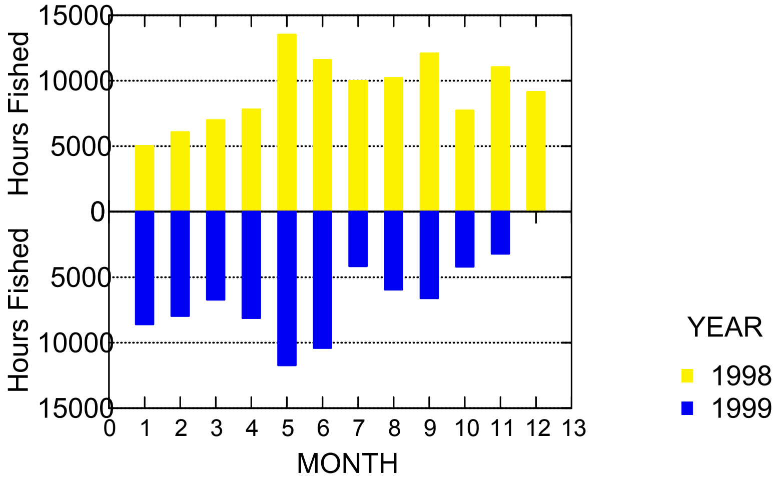

Longitude
-76
-74
-72
-70
-68
-66
42.5
41.2
39.9
38.6
37.3
36.0
Latitude
Latitude
1999
Fishing Time
hours/nm^2
blue <2
green 2-9
yellow 9-44
red >44
Fishing Time 1999
Longitude


Longitude
-76
-74
-72
-70
-68
-66
42.5
41.2
39.9
38.6
37.3
36.0
Latitude
DIFFERENCE PLOT JAN-NOV 1999 minus JAN-NOV 1998
Areas that GAINED effort: red>3.6 hr,ave +67hr, yellow=0 to +3.6hr

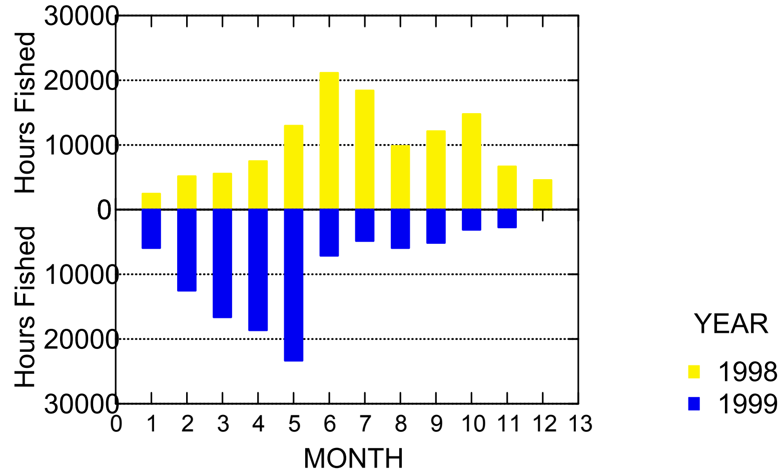

Longitude
-76
-74
-72
-70
-68
-66
42.5
41.2
39.9
38.6
37.3
36.0
Latitude
DIFFERENCE PLOT JAN-NOV 1999 minus JAN-NOV 1998
Areas that LOST effort: blue>5.4 hr,ave -26h, green=0 to -5.4 h

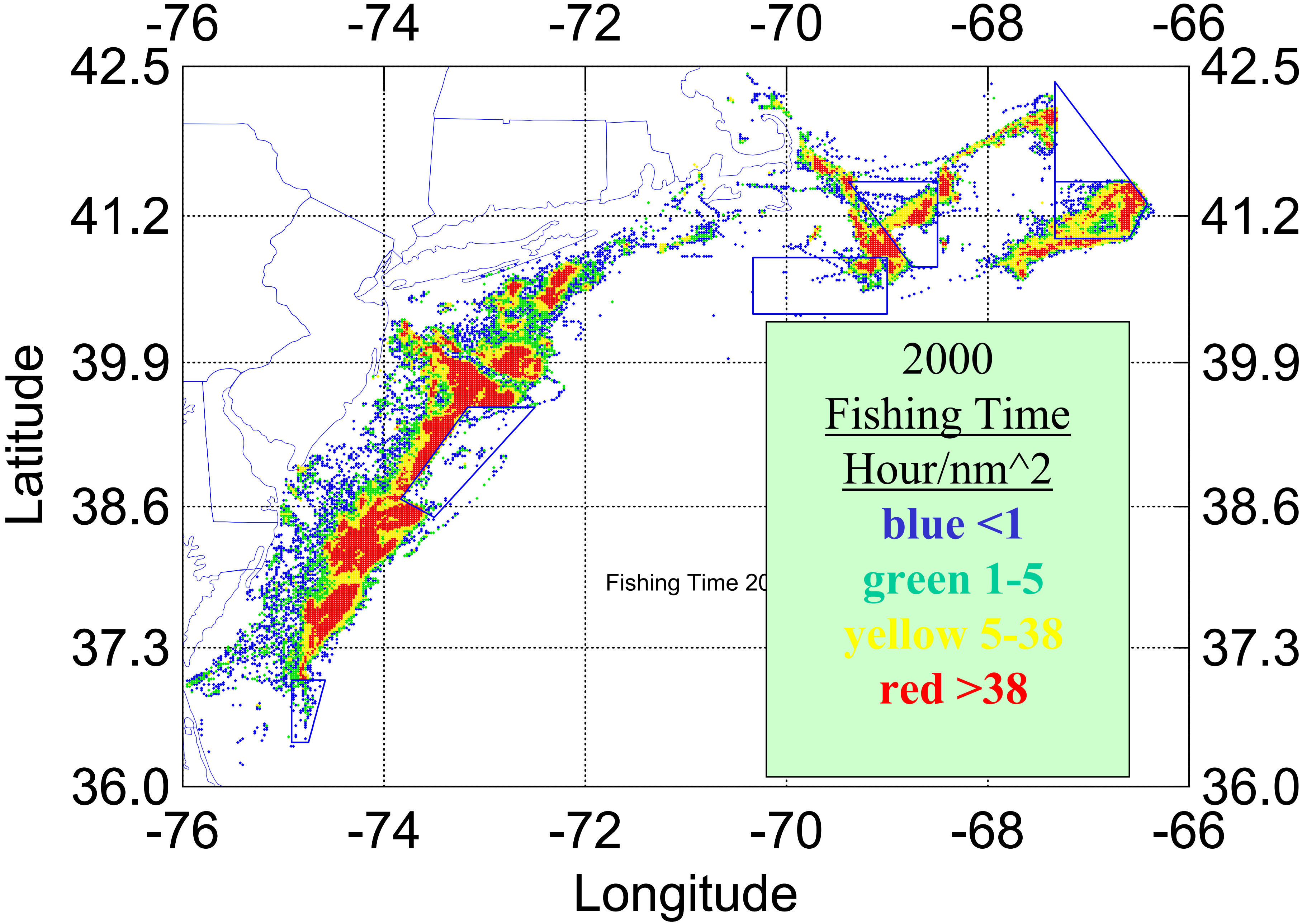
Example of Transfer of Effort from Open to Closed Areas as A result of re-opening of Area II in 1999

1998 vs 99 Effort Comparison: South Channel



1998 vs 99 Effort Comparison: New York Bight




-76
-74
-72
-70
-68
-66
42.5
41.2
39.9
38.6
37.3
36.0
Latitude
Longitude
Fishing Time 20
2000
Fishing Time
Hour/nm^2
blue <1
green 1-5
yellow 5-38
red >38

Tomographic Transformation

VMS raw

j t $x(j,t)$ $y(j,t)$ $s(j,t)$

↓

VMS filtered

j a Δt $x_C(j,\Delta t)$ $y_C(j,\Delta t)$ $s_C(j,\Delta t)$

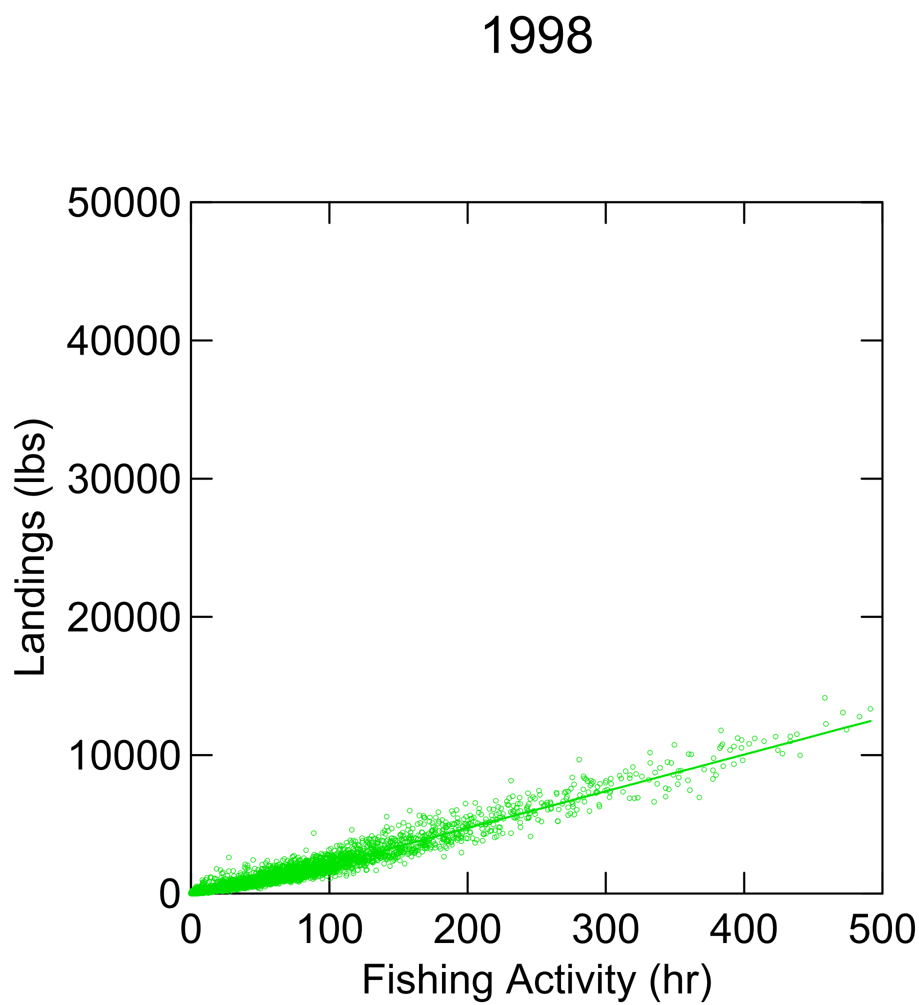
Landings/Revenue (trip)

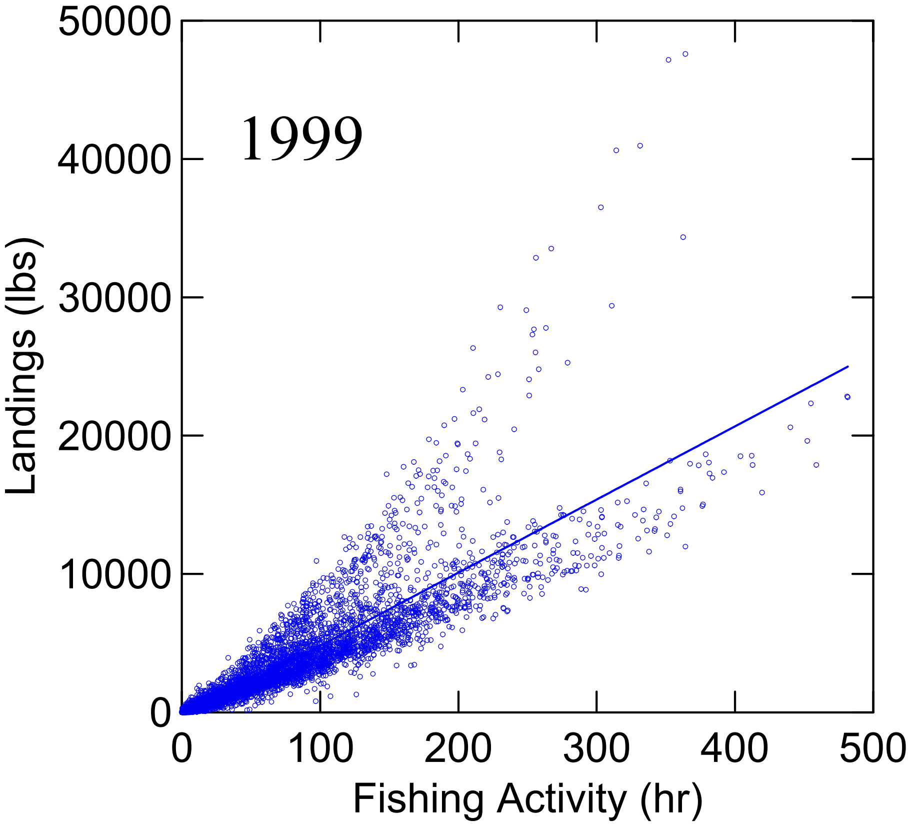
j trip $L(j, \text{trip})$ $R(j,\text{trip})$

↓

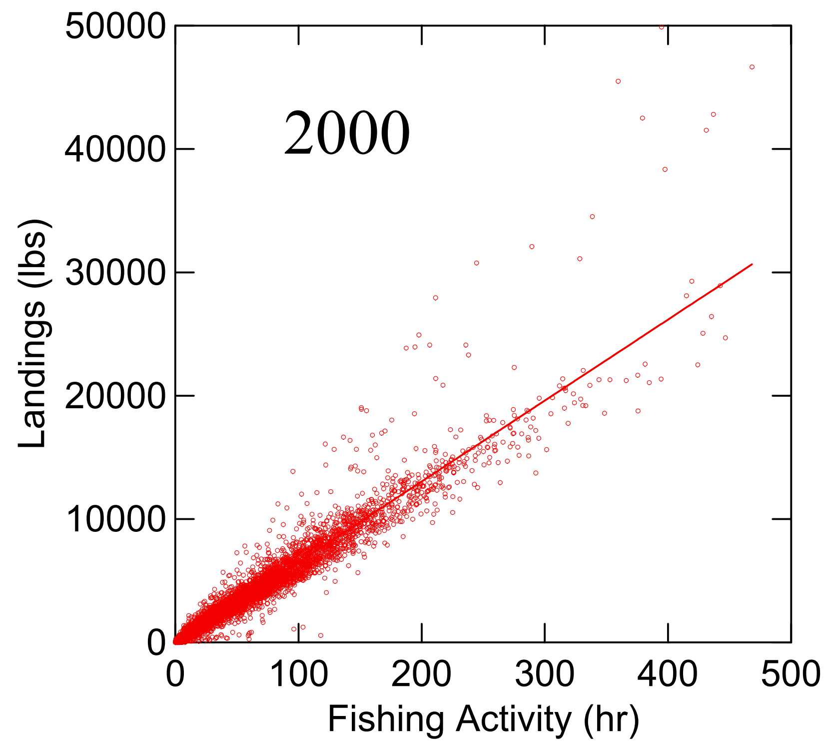
Spatial Effort, Landings, Revenue

c Δt $x_C(\Delta t)$ $y_C(\Delta t)$ $T_C(\Delta t)$ $L_C(\Delta t)$ $R_C(\Delta t)$

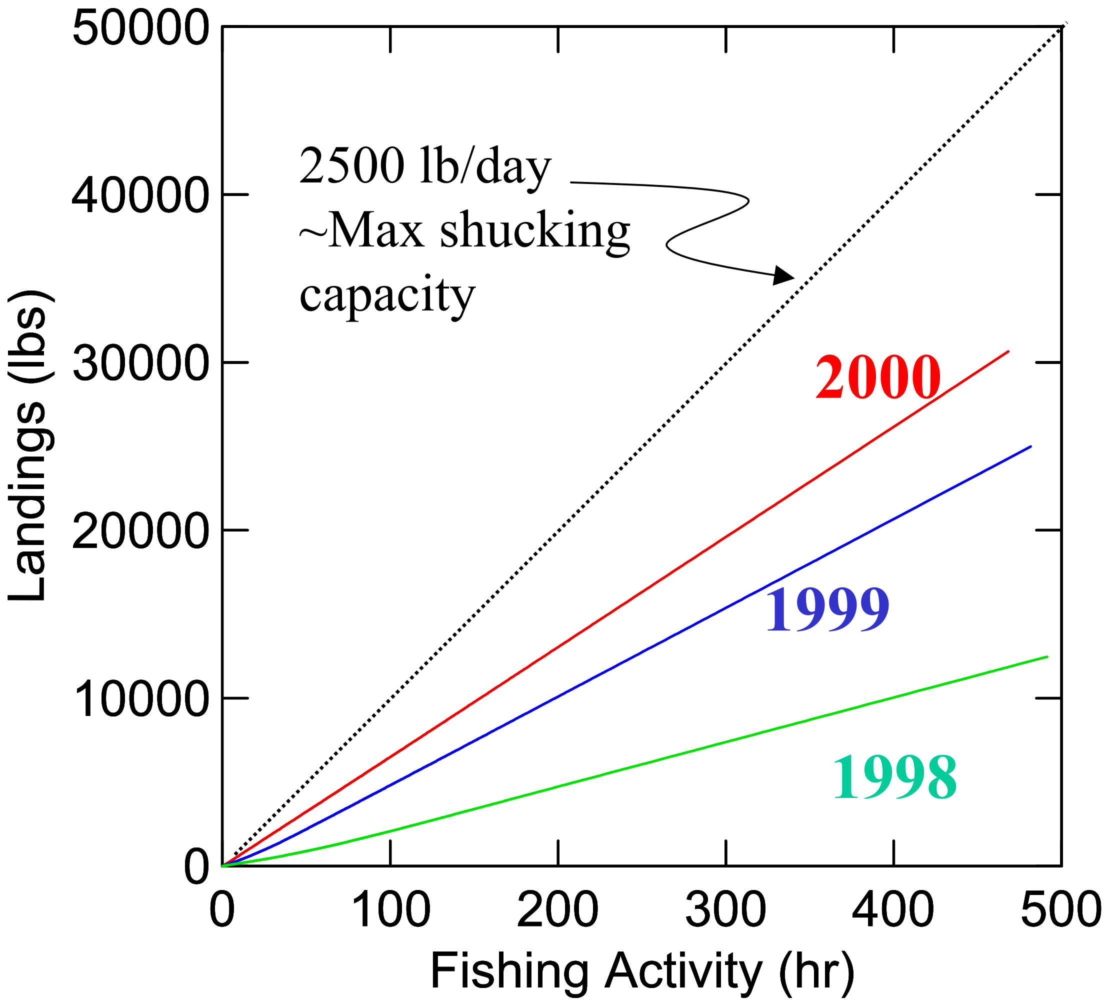



1999
Landings (lbs)
Fishing Activity (hr)
0
10000
20000
30000
40000
50000
100
200
300
400
500

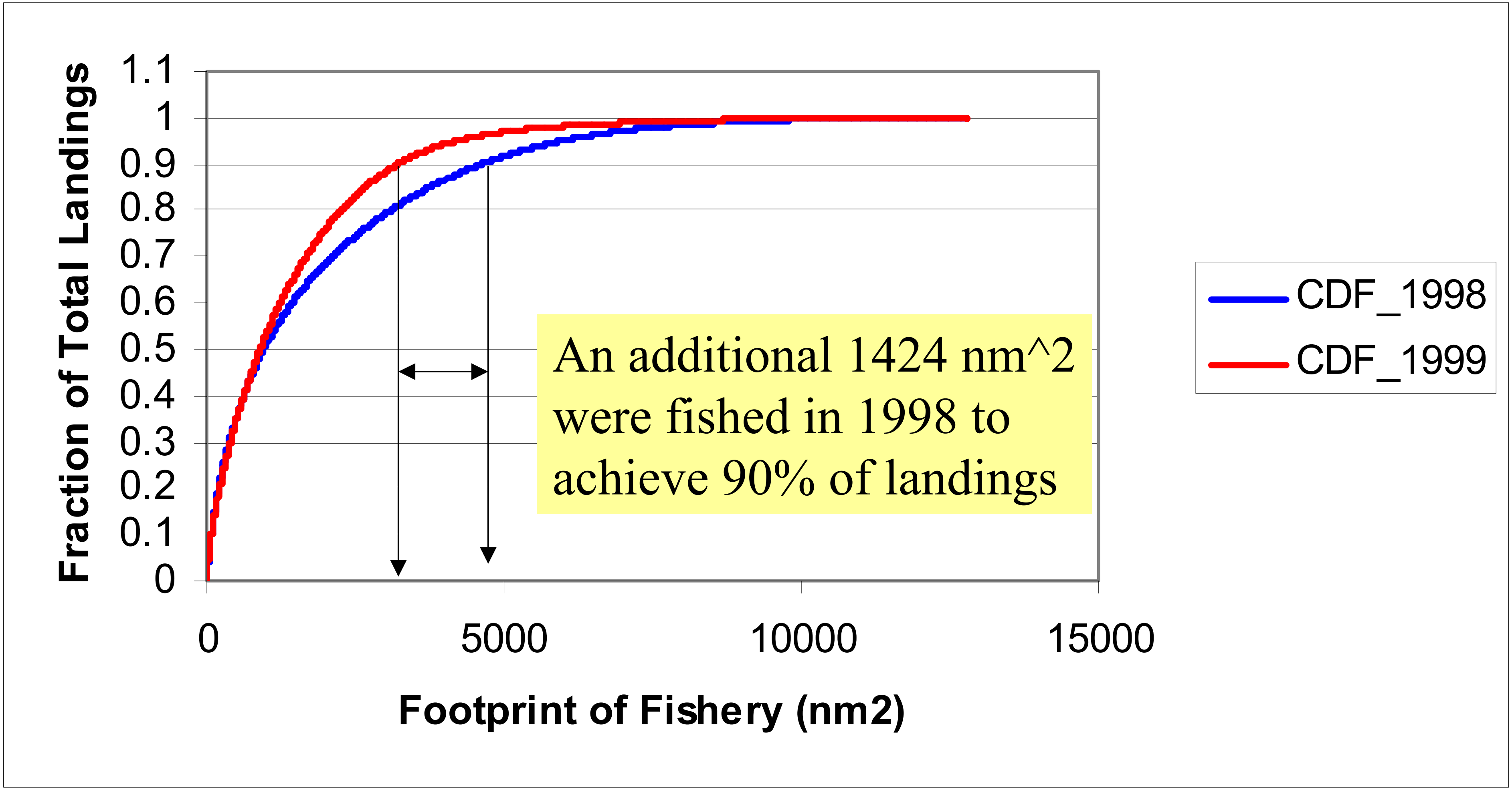
2000

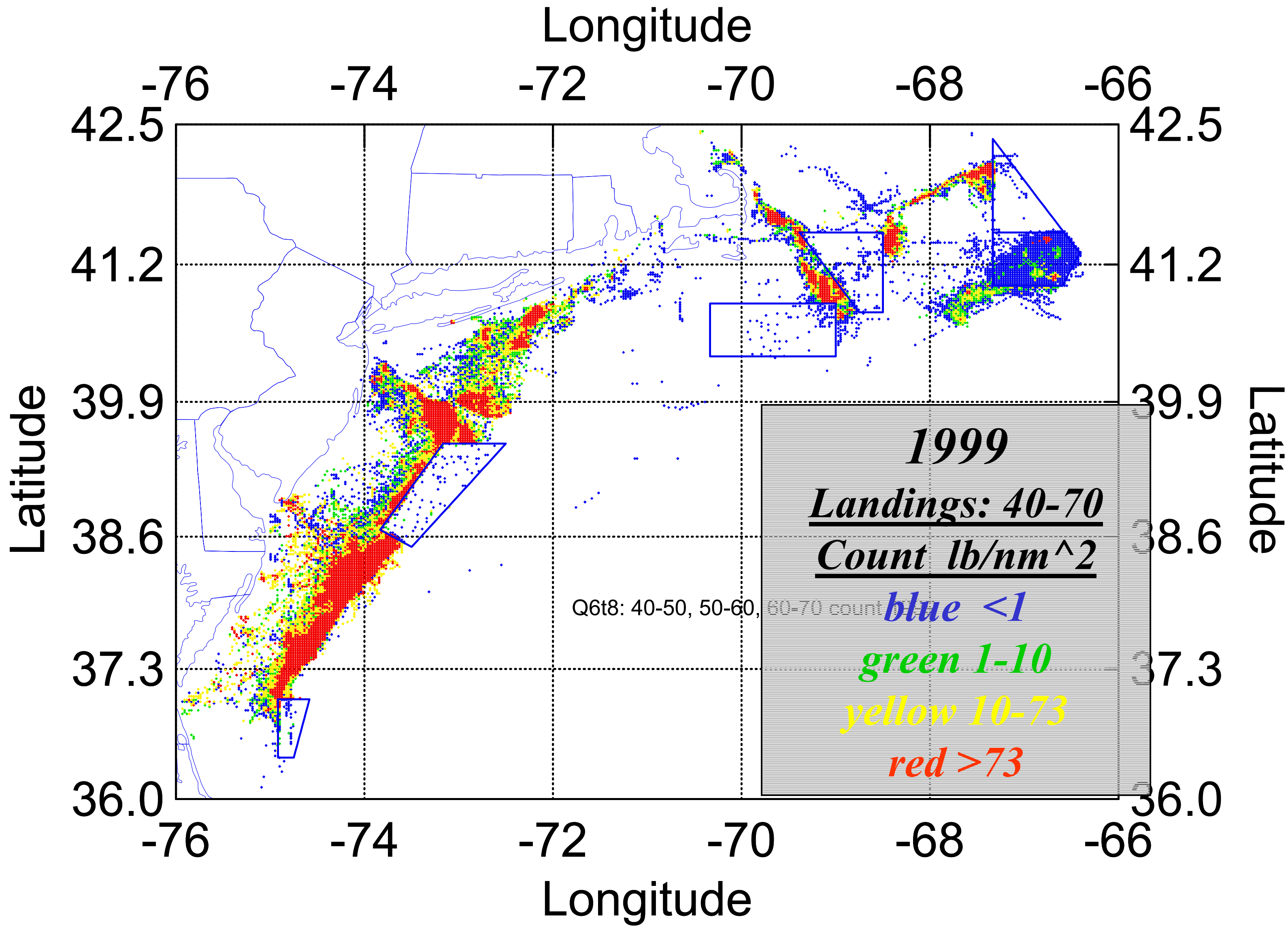

2000
Landings (lbs)
Fishing Activity (hr)
0
10000
20000
30000
40000
50000
100
200
300
400
500

Landings per sqr. Mile vs Fishing Activity (hr)



Comparison of Concentration Curves for Landings in a low density year 1998 and 1999, a year in which landings were augmented by access to the Closed Area II.





Longitude
-76
-74
-72
-70
-68
-66
42.5
41.2
39.9
38.6
37.3
36.0
Latitude
1999
Landings: 40-70
Count lb/nm^2
blue <1
green 1-10
yellow 10-73
red >73
Q6t8: 40-50, 50-60, 60-70 count

Myths and Facts about Multi-objective Optimization Methods (MOM)

MYTH

- Optimization gets you the maximum for the minimum
- MOM requires that all objectives have same units of measure
- MOM requires agreement on the relative value on each objective
- MOM give useless advice

FACT

- Optimization finds max or min subject to constraints
- Non-commensurate objectives can be used: eg: $ vs Acres
- All possible relative values are evaluated
- MOM can point you in the right direction.

Quartile Analyses

A simple way to identify tradeoffs

Assign observation to quartile for each variable. Then count number of cells in the joint density table. In this hypothetical example, there is a large potential to establish tradeoffs since the cells with the highest scallop yields are also the sites with lowest bycatch.

		Scallop Yield			
		Q1	Q2	Q3	Q4
Bycatch	Q1	10	50	75	600
	Q2	20	80	600	60
	Q3	60	500	50	30
	Q4	500	70	15	5

Quartile Analyses

Each cell in the table identifies a collection of areas that satisfy the criteria for scallop yield and bycatch. A simple plot of these data should be sufficient to identify possible tradeoff areas. In this hypothetical example, there is a LOW potential to establish tradeoffs since the cells with the highest scallop yields are also the sites with HIGHEST bycatch.

		Scallop Yield			
		Q1	Q2	Q3	Q4
Bycatch	Q1	700	50	75	20
	Q2	20	650	50	60
	Q3	30	40	500	30
	Q4	10	5	15	500

Multi-Objective Linear Programming

A relatively simple way to compare tradeoffs between objectives

Key Elements:

Quantifiable Objective,

Decision Variables,

Constraints

$D_{i,j} =$ Decision variable for area i, j

where $D_{i,j} = 1$ if area is open to fishing, else $=0$

$V_{s,i,j} =$ Value of species s in area i, j.

where $V_{s,i,j} = f(\text{biomass, impact potential, etc…})$

Defining Objectives and Constraints

Objective Function for the set {E} of species or attributes that are enhanced by fishery,

$$\sum_{s \in E} \sum_{i} \sum_{j} D_{i,j} V_{s,i,j}$$

Objective Function for the set {I} of species or attributes that are dimished/degraded/impacted by fishery.

$$\sum_{s \in I} \sum_{i} \sum_{j} (1 - D_{i,j}) V_{s,i,j}$$

Evaluating Multiple Objectives

It is not necessary for the two objective functions to have commensurate values. Each objective function is weighted by an arbitrary value π_m such that $\sum \pi_m = 1$. For a simple problem with two objectives, the optimization model can be written as:

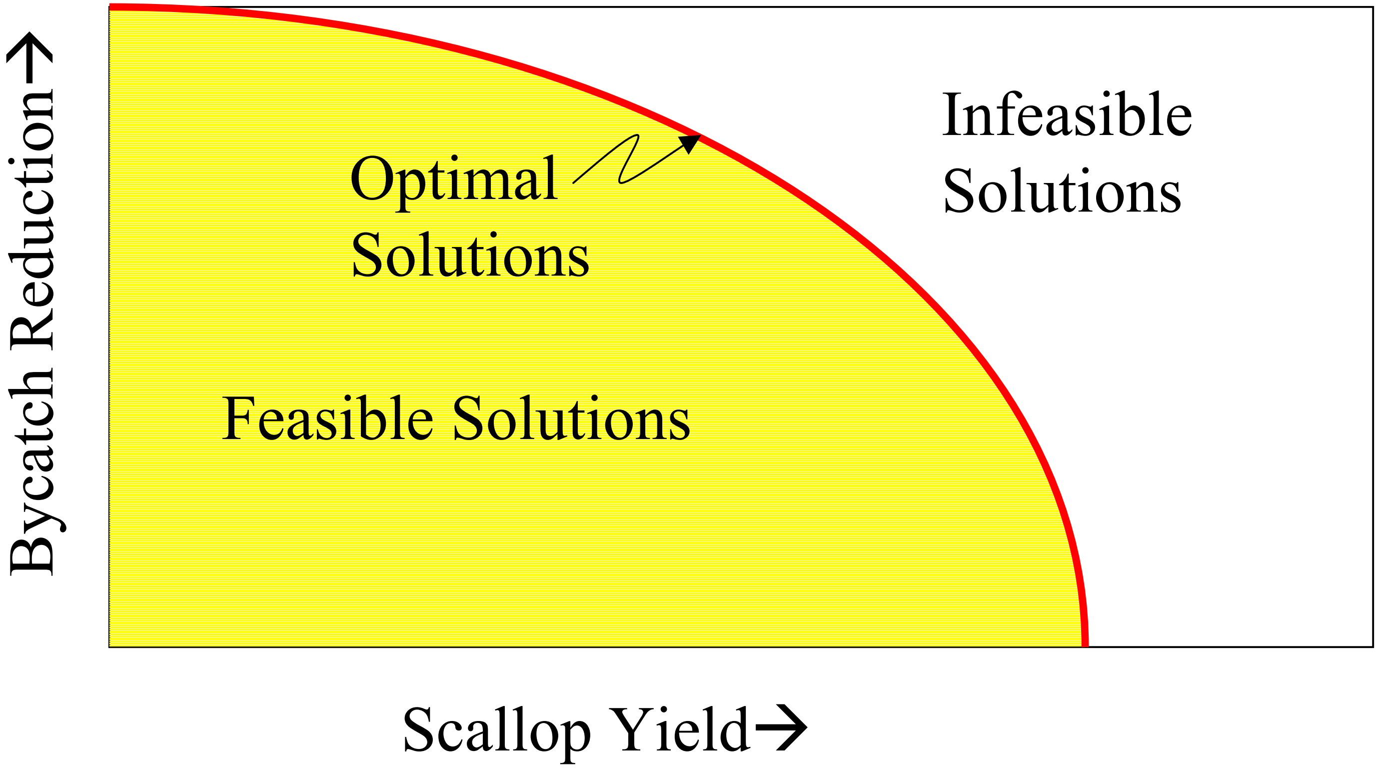
$$\text{Maximize } \{\pi \sum_{s \in E} \sum_{i} \sum_{j} D_{i,j} V_{s,i,j} + (1\text{-}\pi) \sum_{s \in I} \sum_{i} \sum_{j} (1 - D_{i,j}) V_{s,i,j} \}$$

Subject to: $0 < D_{i,j} < 1$, and other constraints

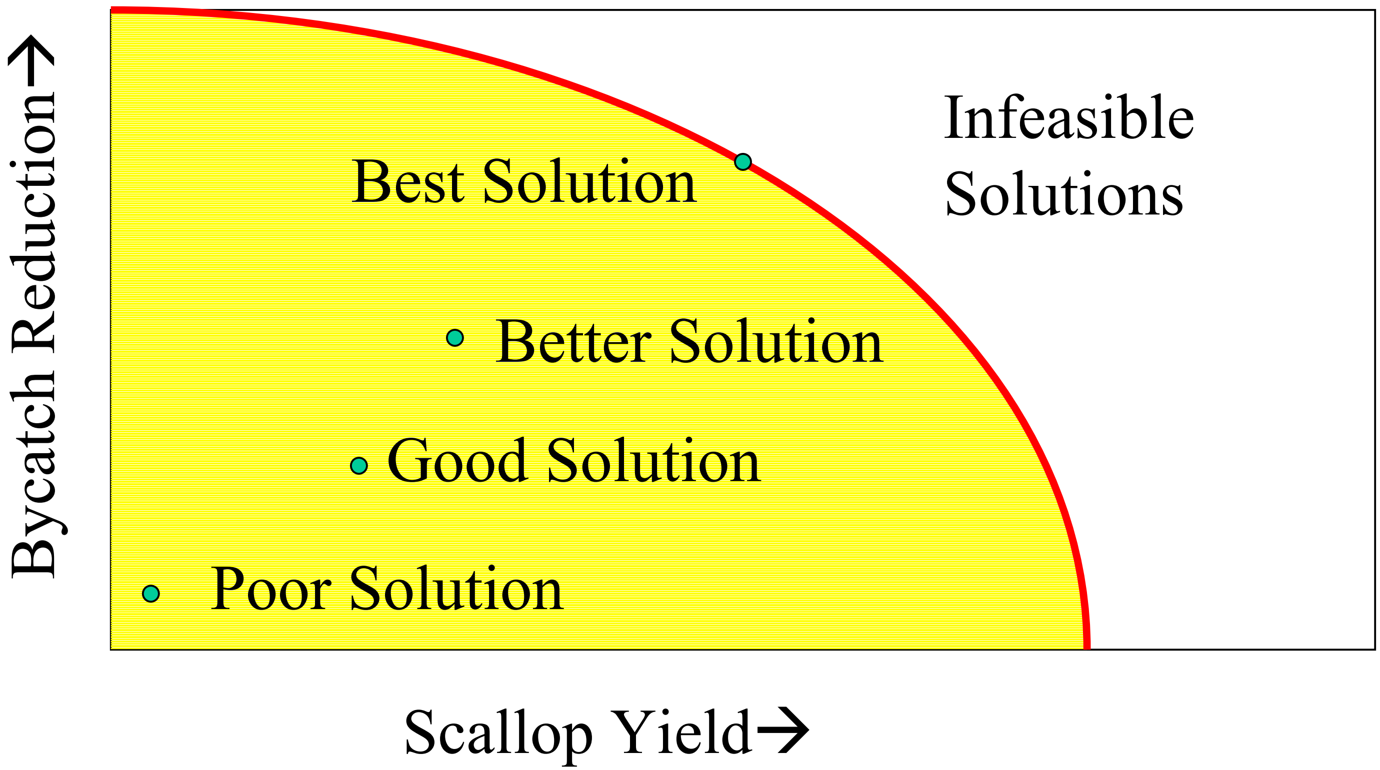
Evaluating All Possible Alternatives

- It is not necessary to derive the relative value or merit of each objective function component. This is the subject of endless and divisive debate and source of amusement to outsiders.
- Instead, one examines the value of the objective function over the full range of relative values of π between 0 and 1.
- The resulting set of optimal solutions define the Pareto optimality frontier, a boundary that separates feasible from infeasible solutions, and a benchmark against which specific solutions can be compared.
- The solution set corresponding to a point on the Pareto boundary can be used as starting points for the development of a particular solution in which non-quantifiable or difficult to quantify factors are incorporated

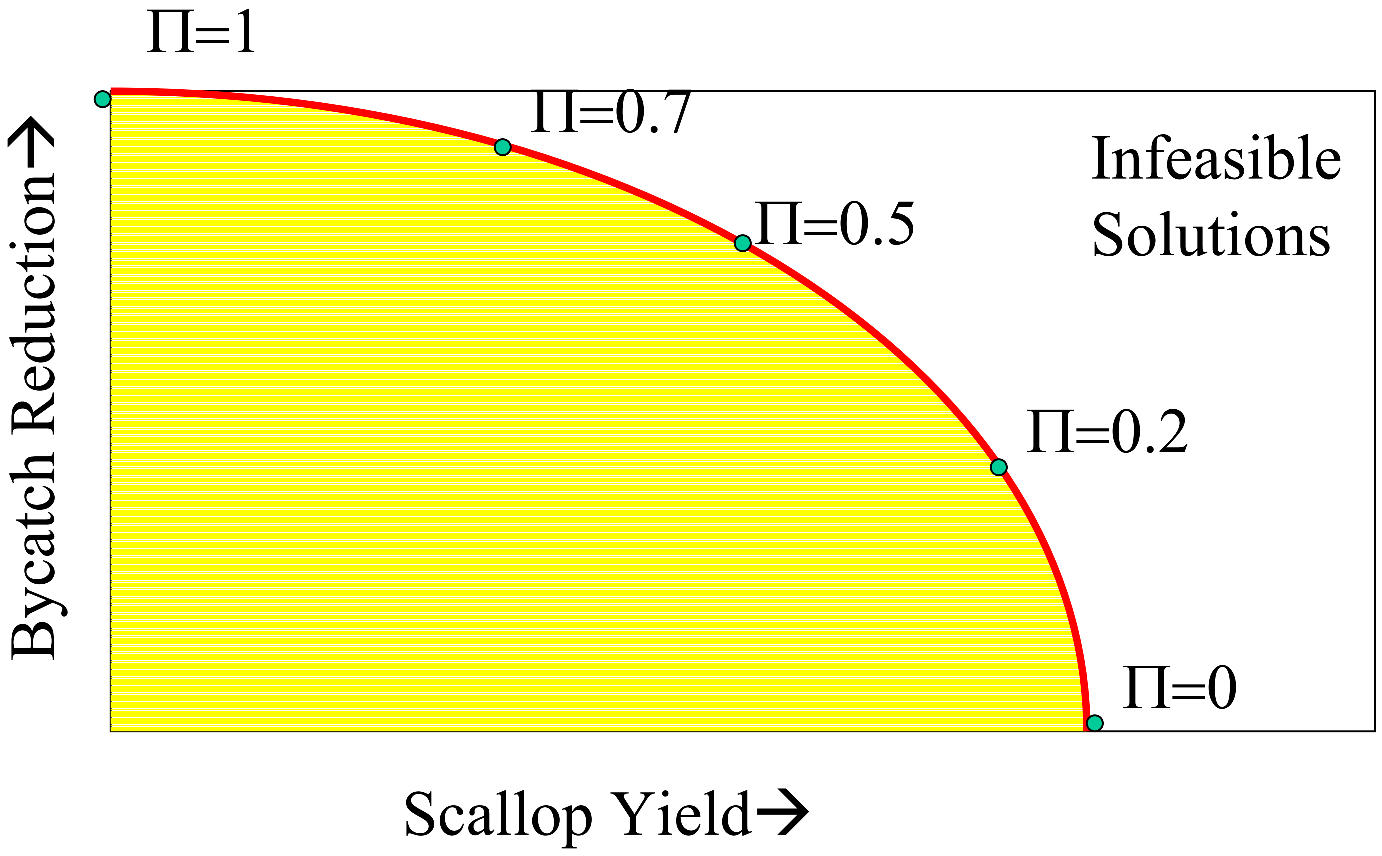
Classic Economic Choices:
Guns vs Butter—Swords vs Plowshares—
Scallops vs Bycatch



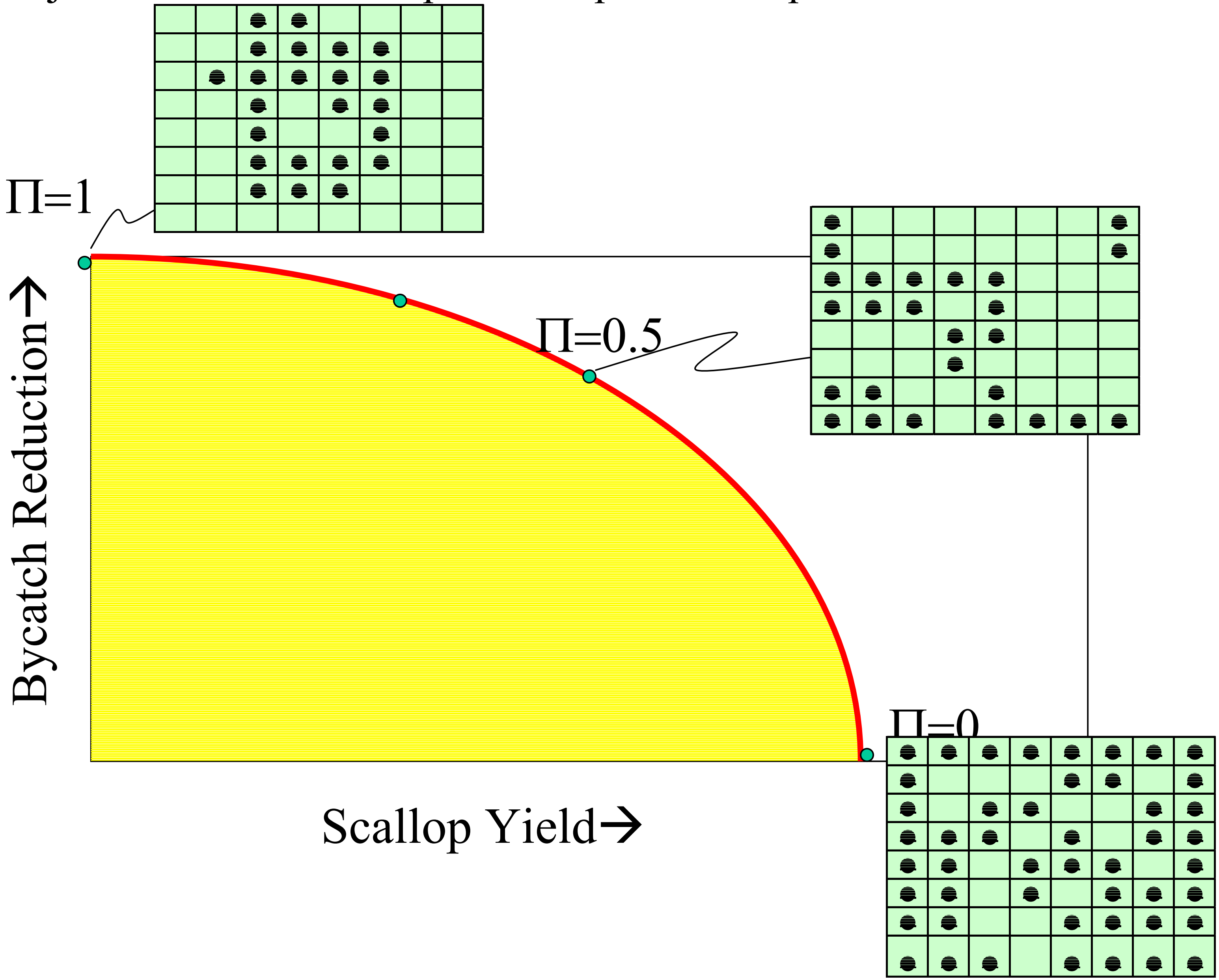
Solutions that approach the boundary are better than those near the origin because more of one or more of the objectives is attained



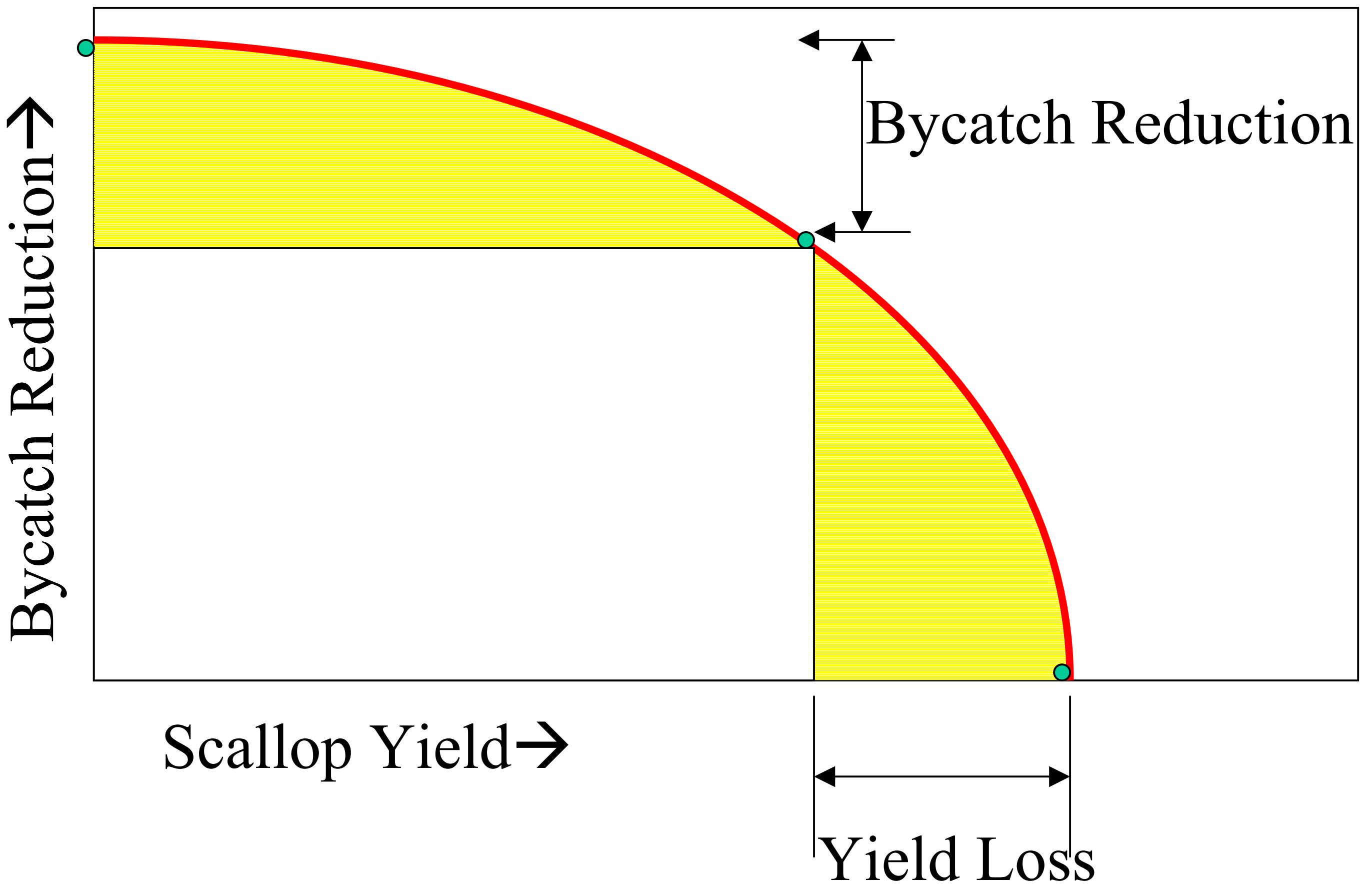
Solutions on the boundary represent the set of possible weighting of the objective function



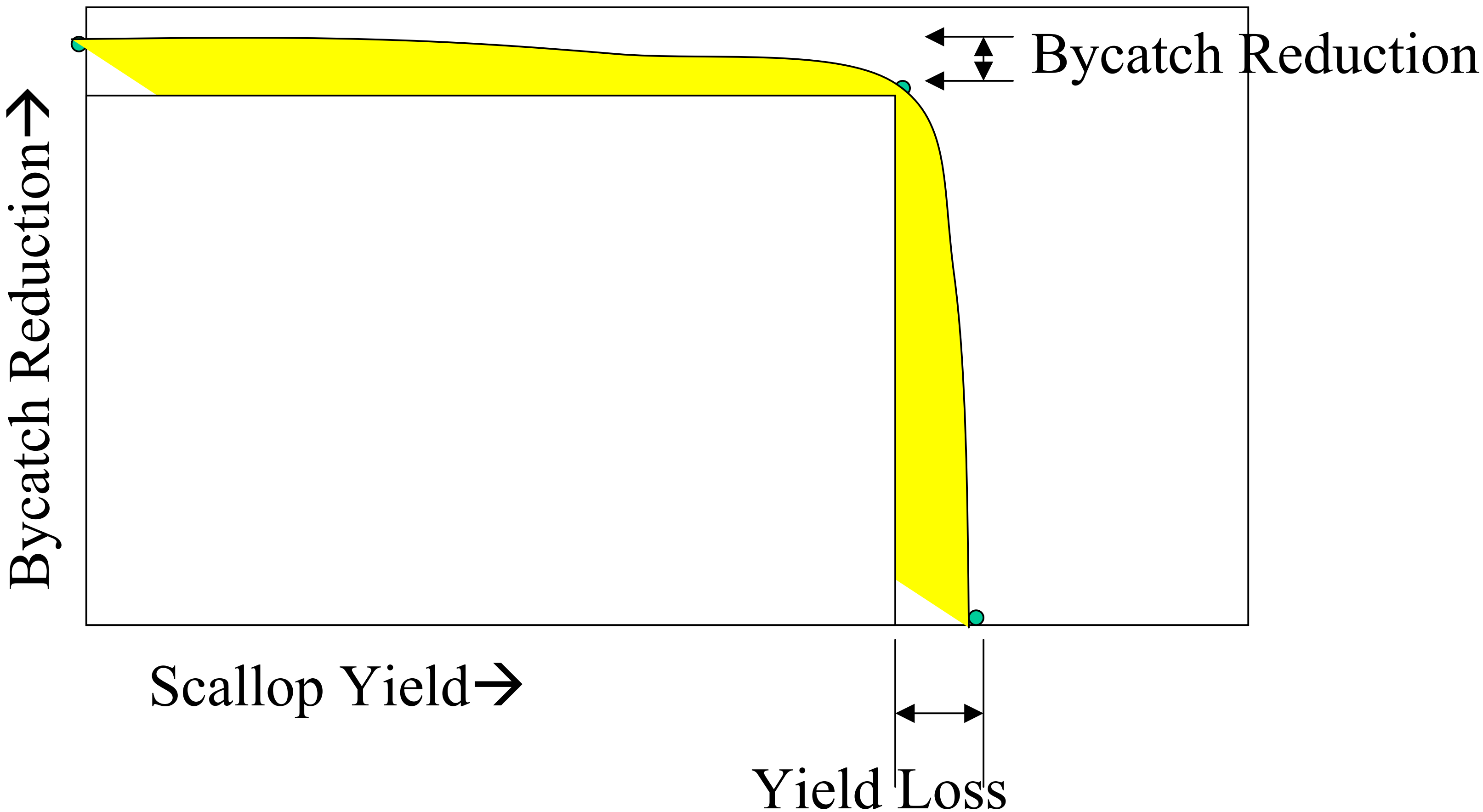
Solutions on the boundary represent the set of possible weighting of the objective function and a particular pattern of open and closed areas.



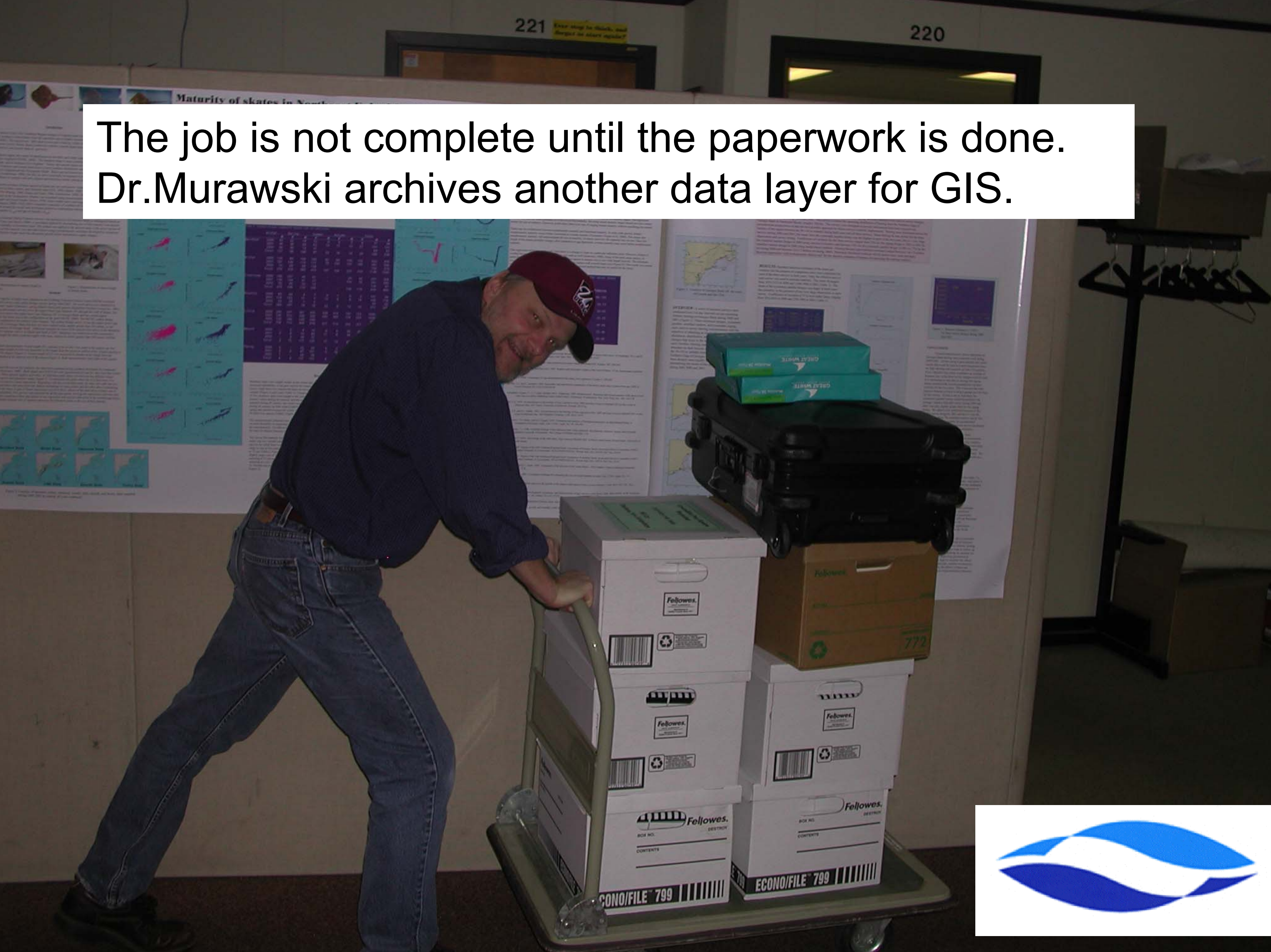
Alternative Solutions can be evaluated with respect to the attainment of maximum values that would be possible in the absence of additional objectives. Acceptable solutions are those that are acceptable to all parties

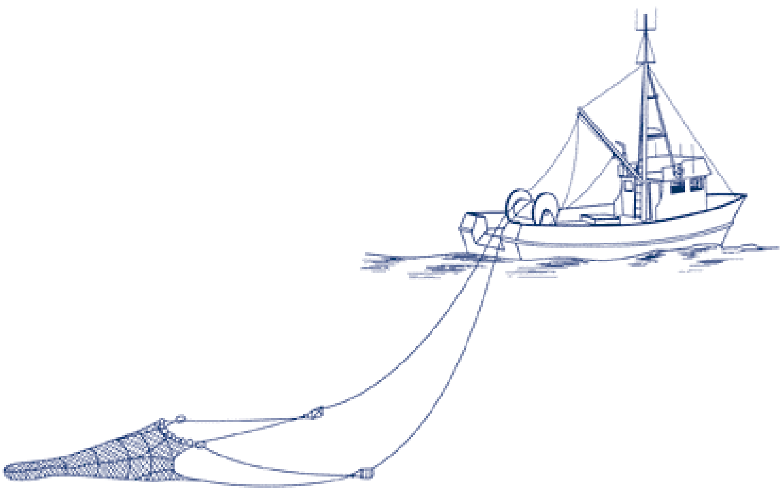


“Steeper” Solutions on the boundary represent the ideal situation: Both objective functions are near their maximum values and little has to be given up.



The job is not complete until the paperwork is done.
Dr.Murawski archives another data layer for GIS.

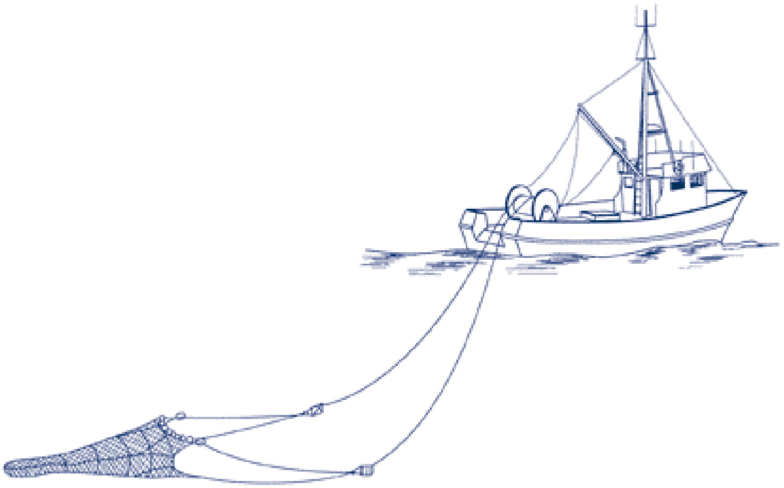




Doveryai, no proveryai,
Russian proverb
Trust, but verify

"life does not stand still while specialists put their minds in order"

Michael Graham, 1950. Address to United Nations



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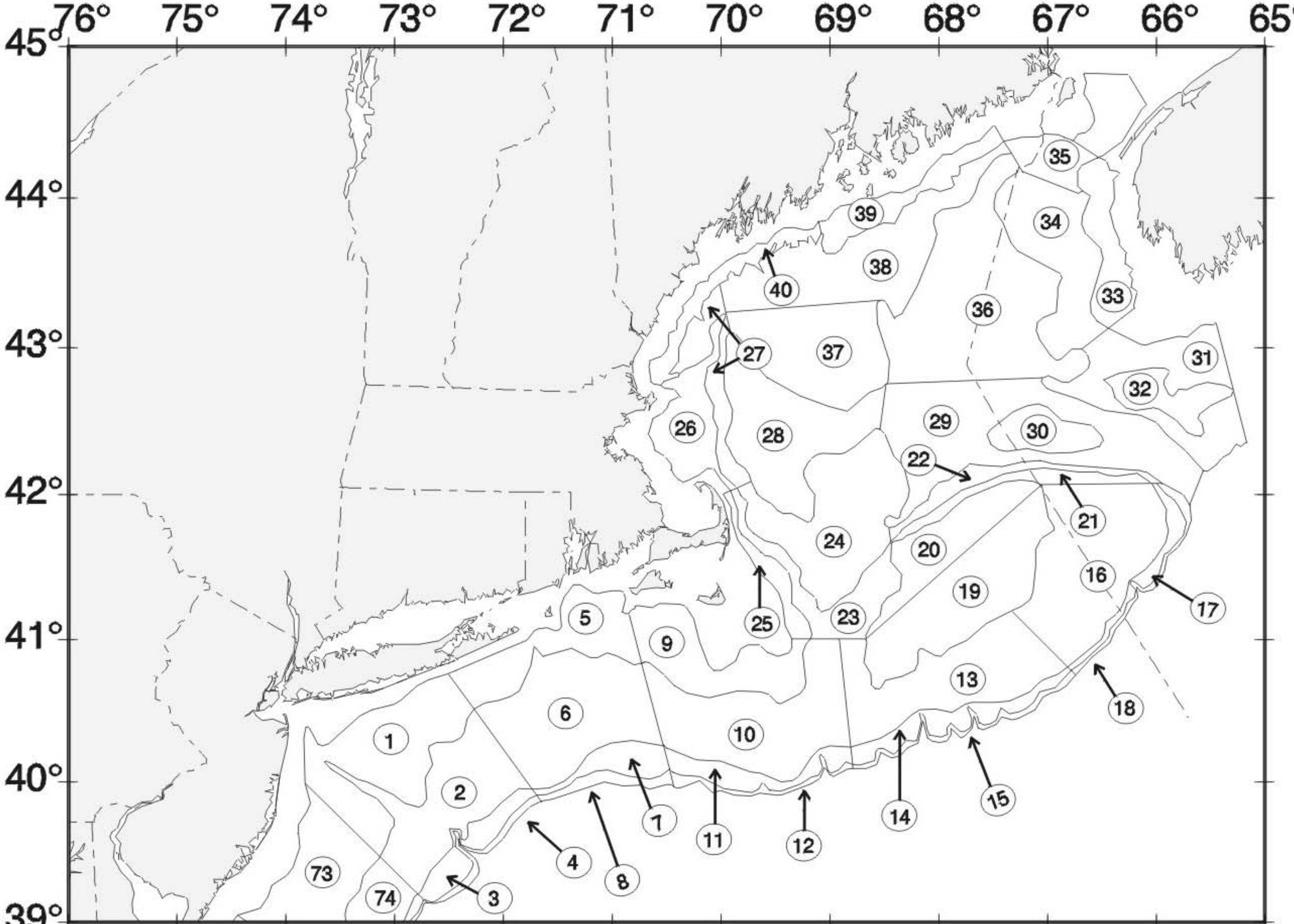
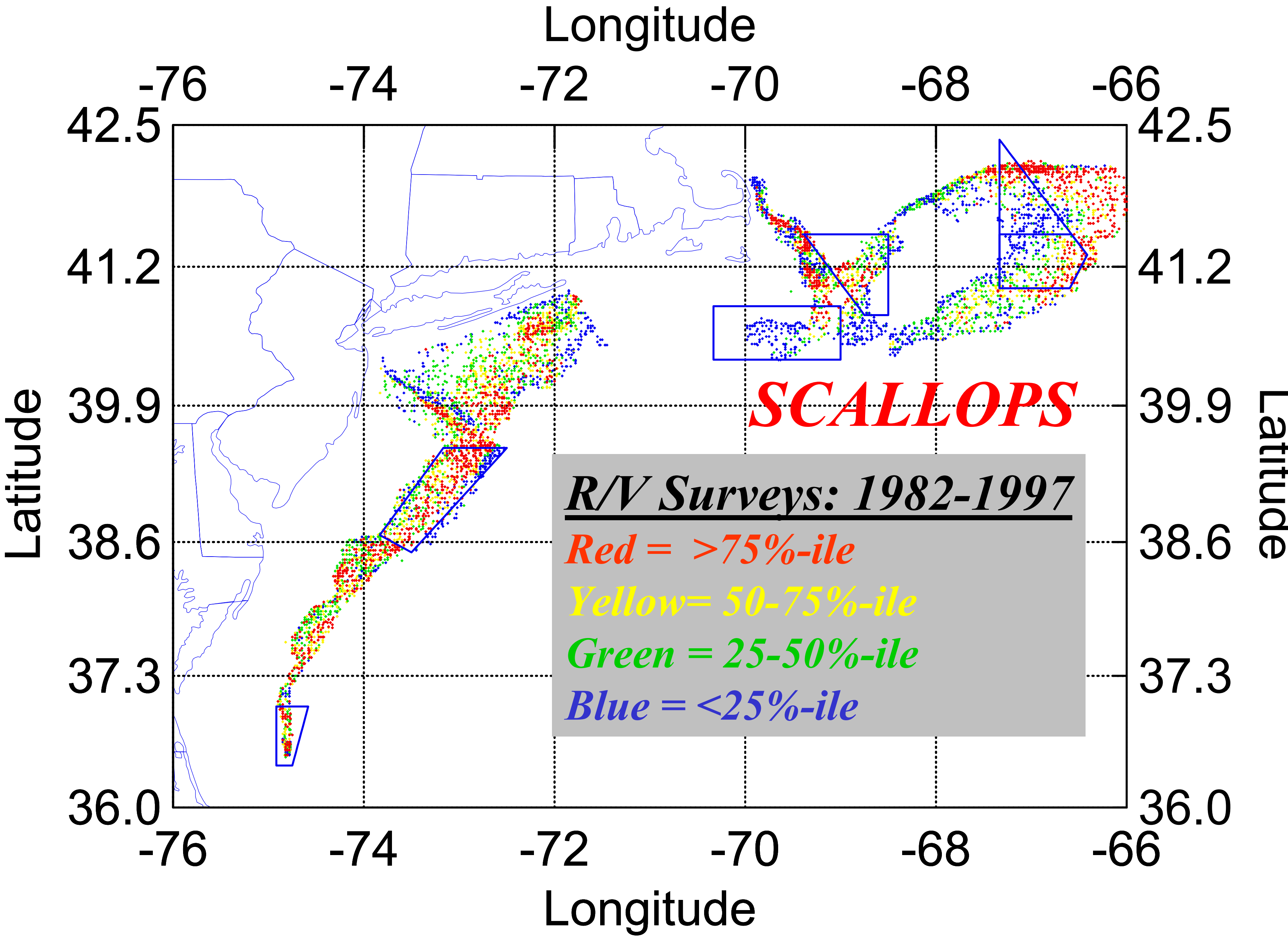
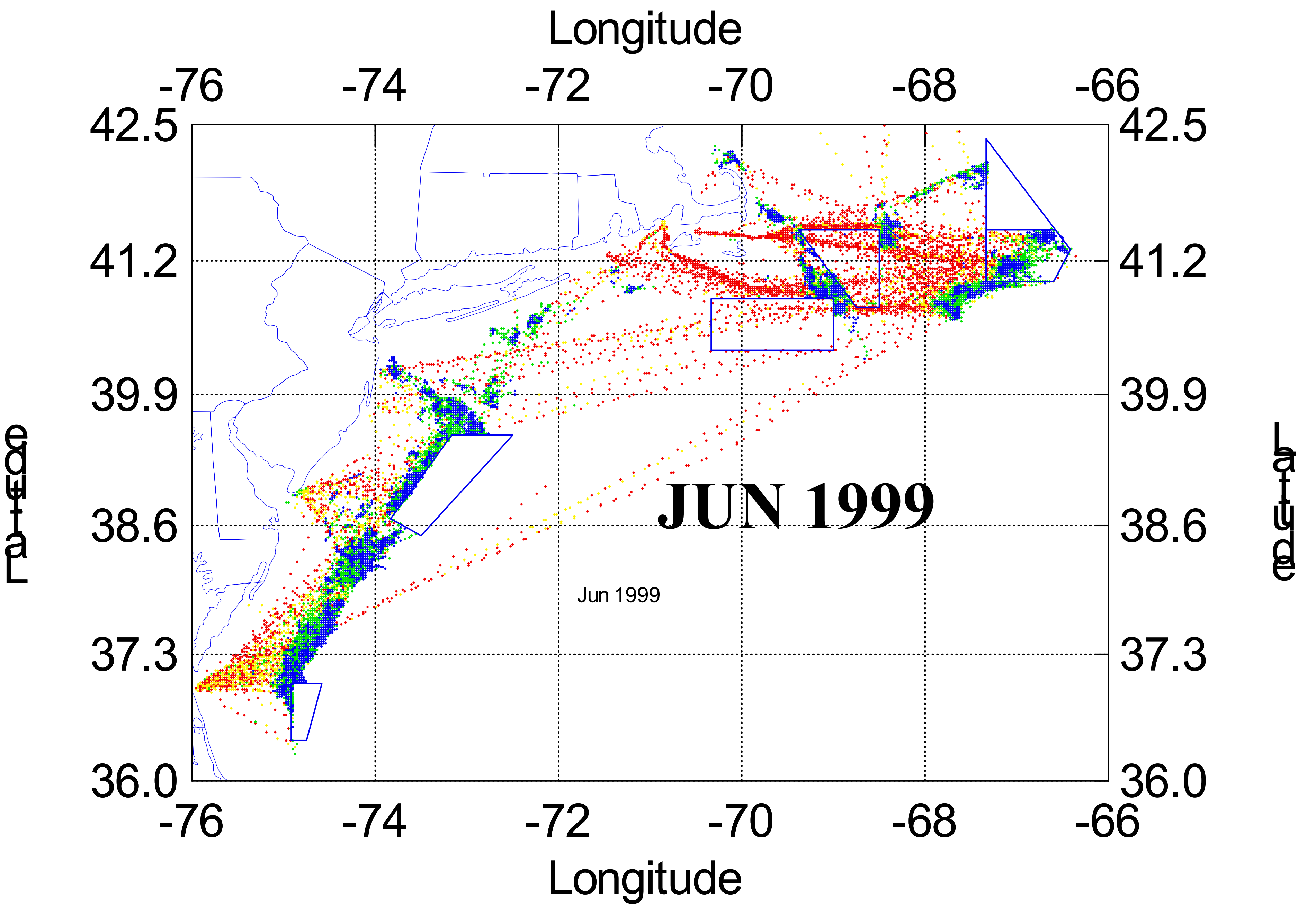
Northern offshore survey strata



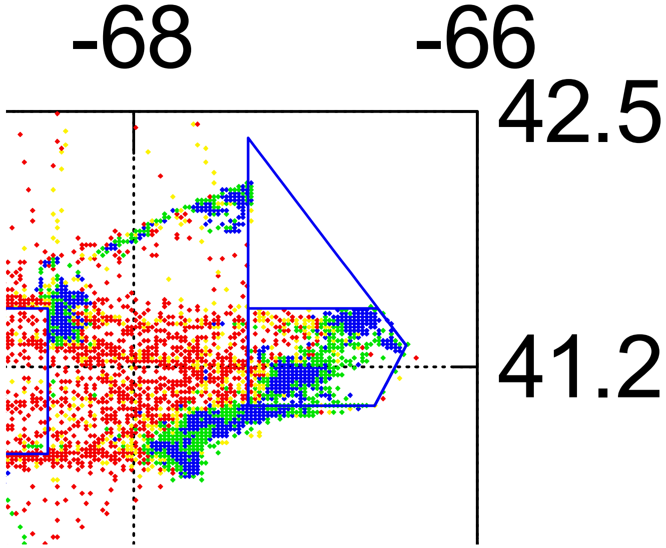
NEFSC Offshore Bottom Trawl Northern Survey Strata

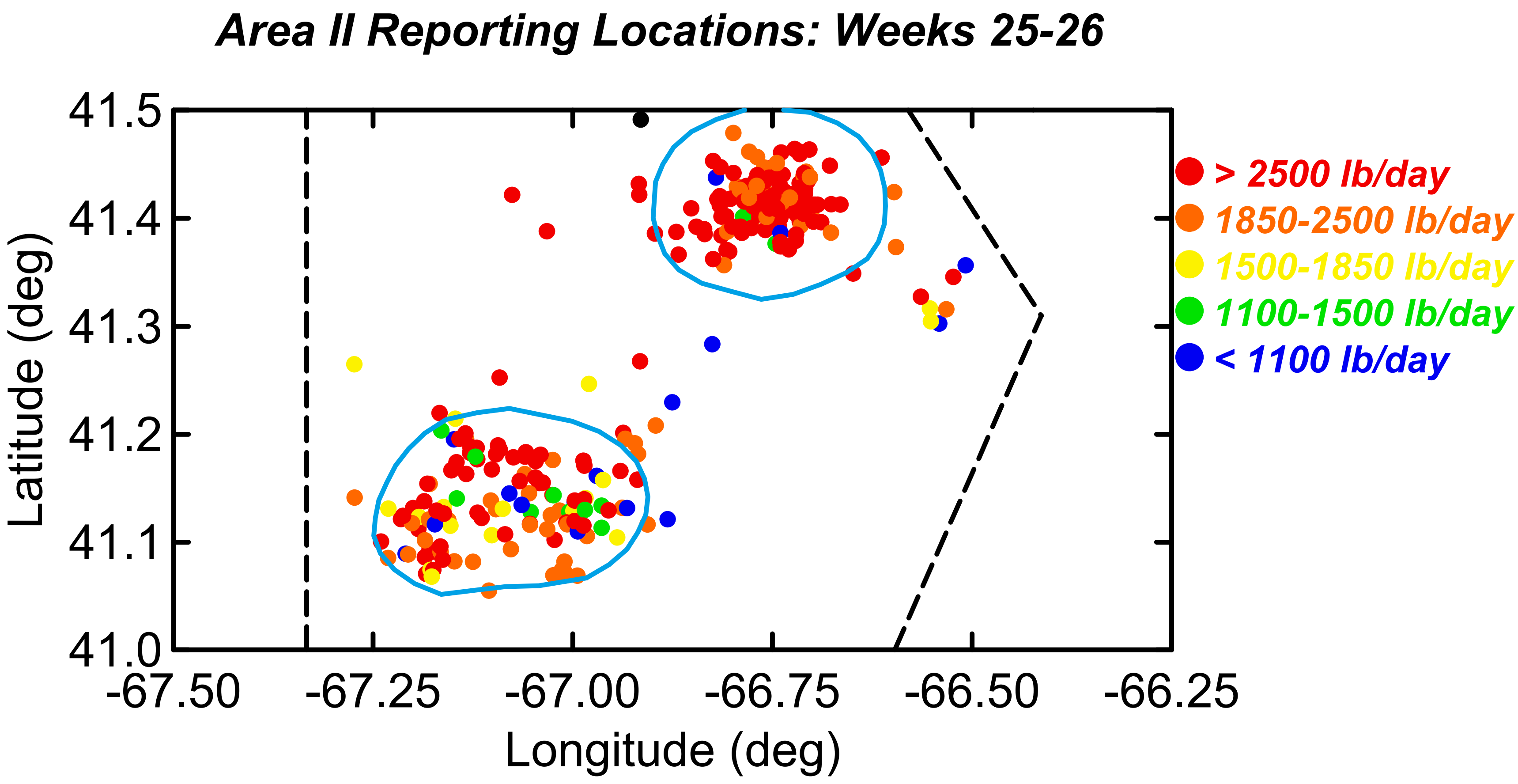


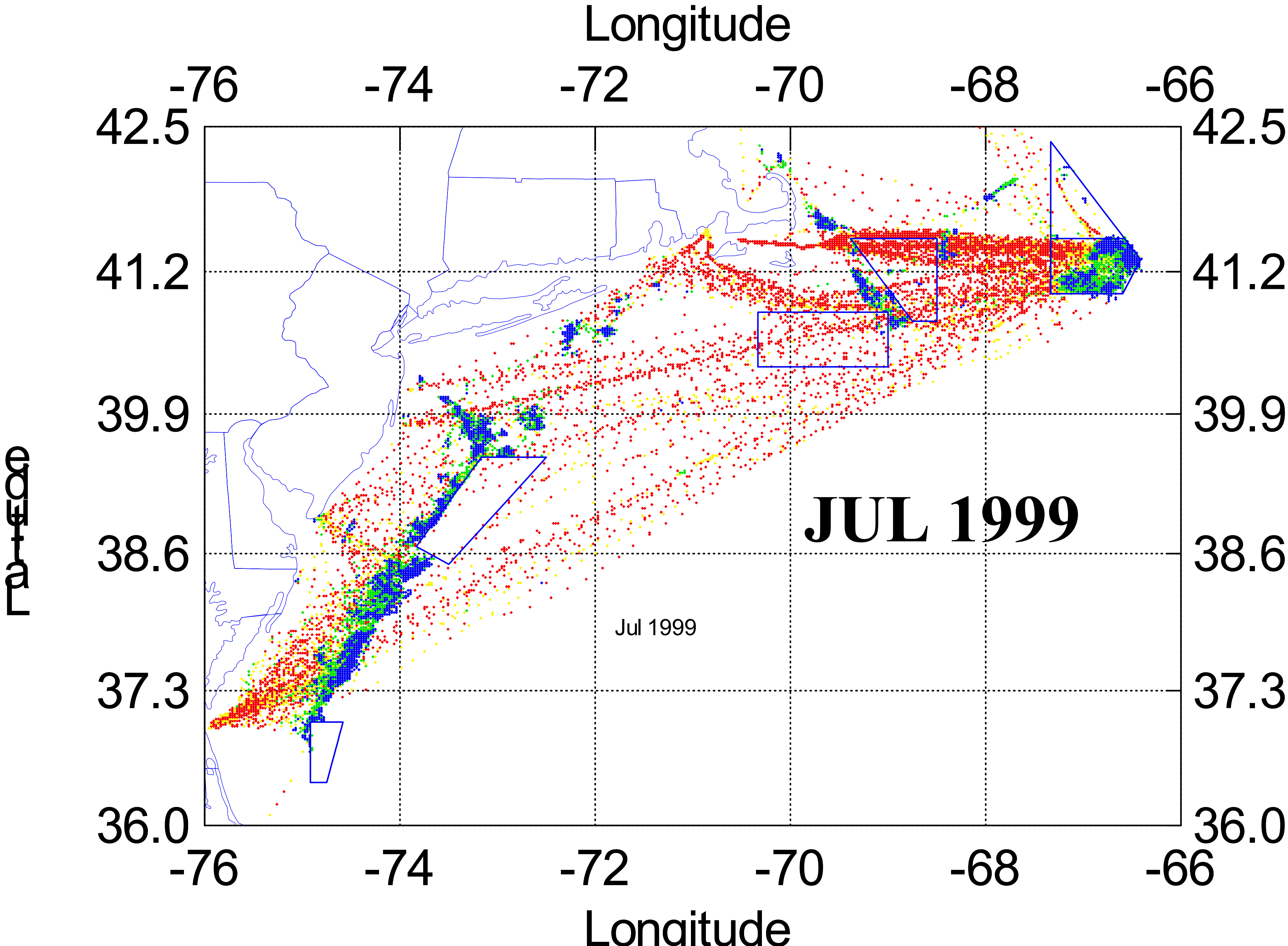
Longitude
-76
-74
-72
-70
-68
-66
42.5
41.2
39.9
38.6
37.3
36.0
Latitude
SCALLOPS
R/V Surveys: 1982-1997
Red = >75%-ile
Yellow= 50-75%-ile
Green = 25-50%-ile
Blue = <25%-ile


Longitude
-76
-74
-72
-70
-68
-66
42.5
41.2
39.9
38.6
37.3
36.0
Latitude
JUN 1999
Jun 1999

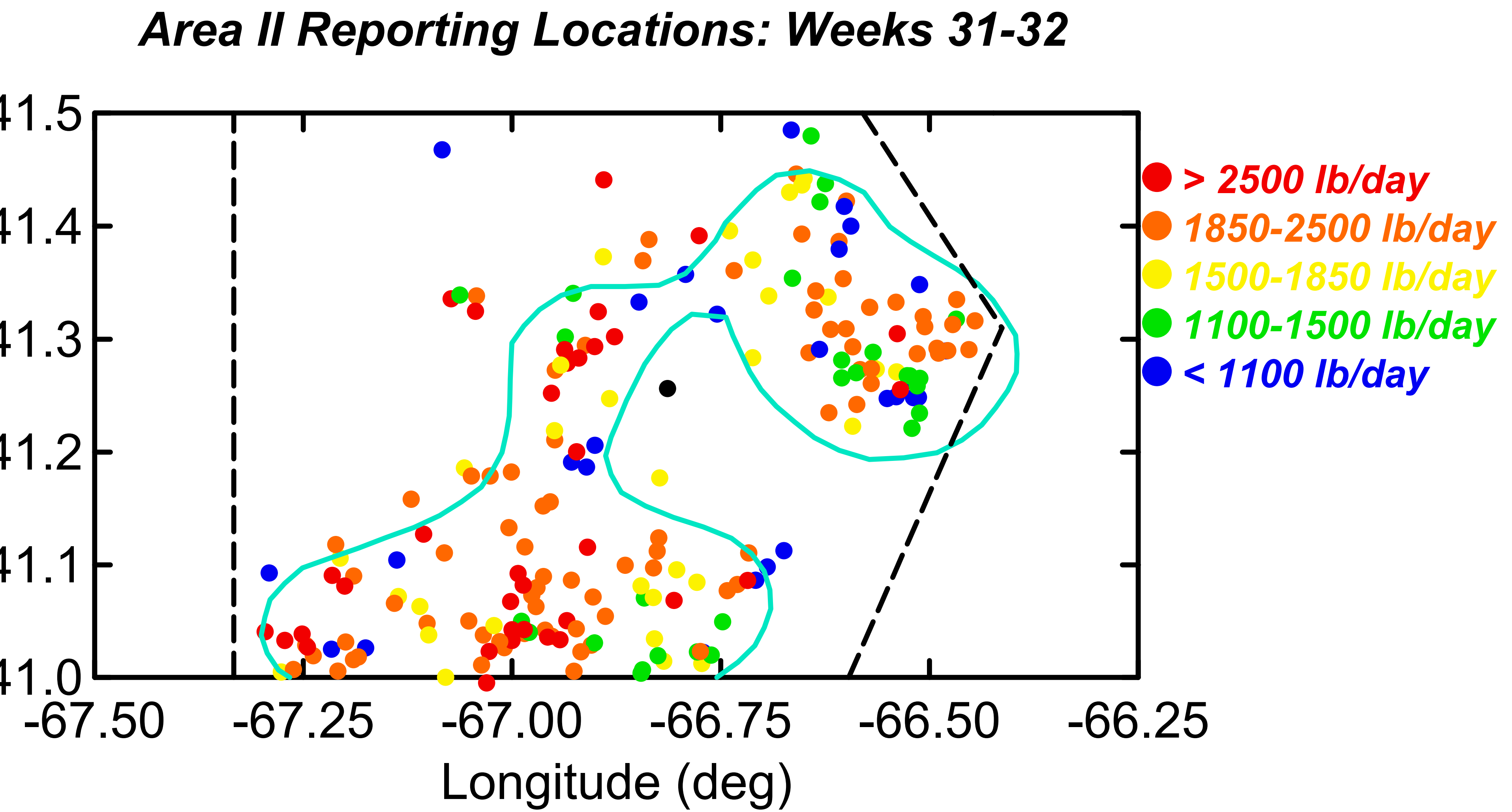
Comparison of scallop VMS fishing activity with Observer Reports of Daily Catch rates. Second two weeks of June 1999. Scallop closed area II access.



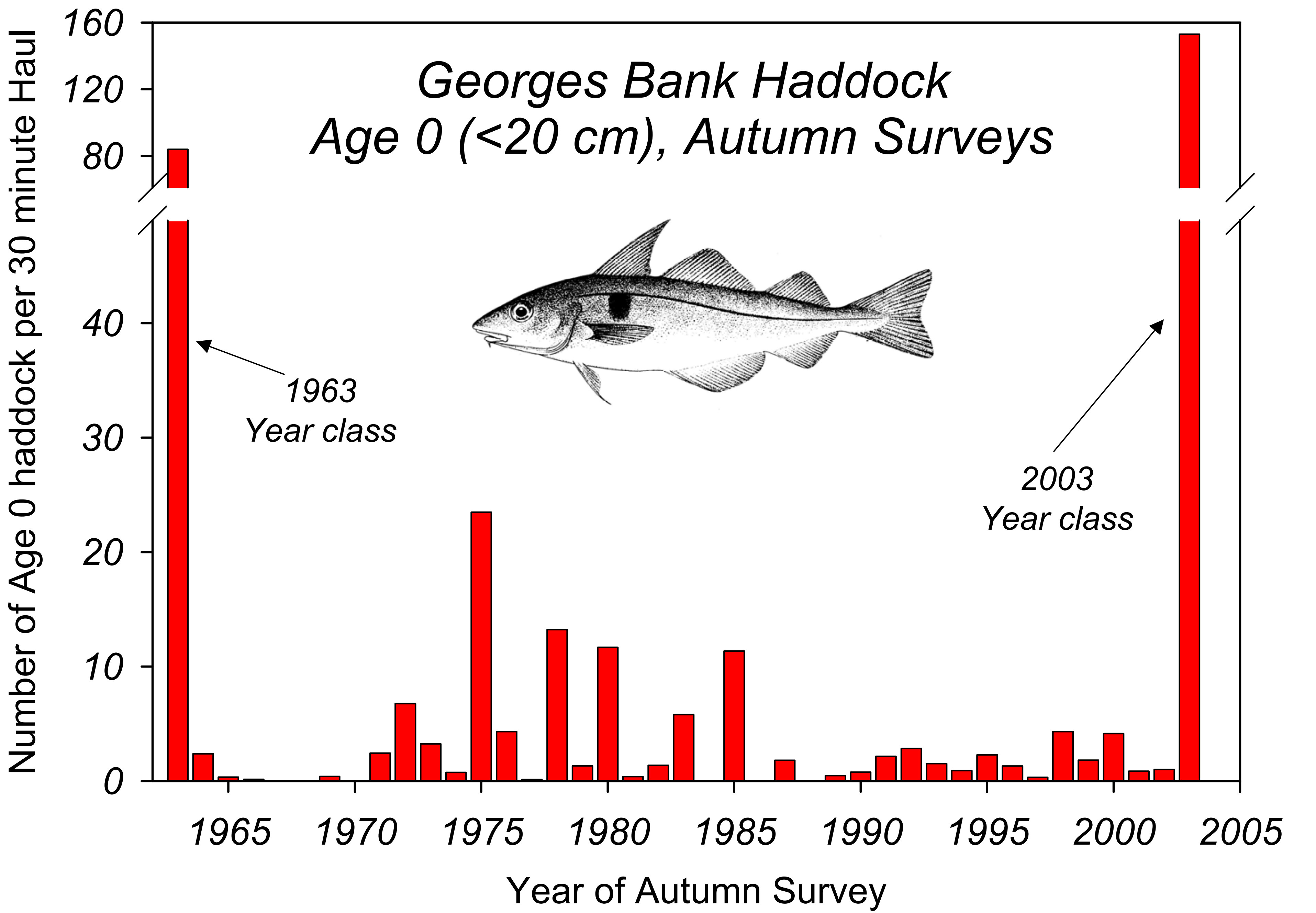




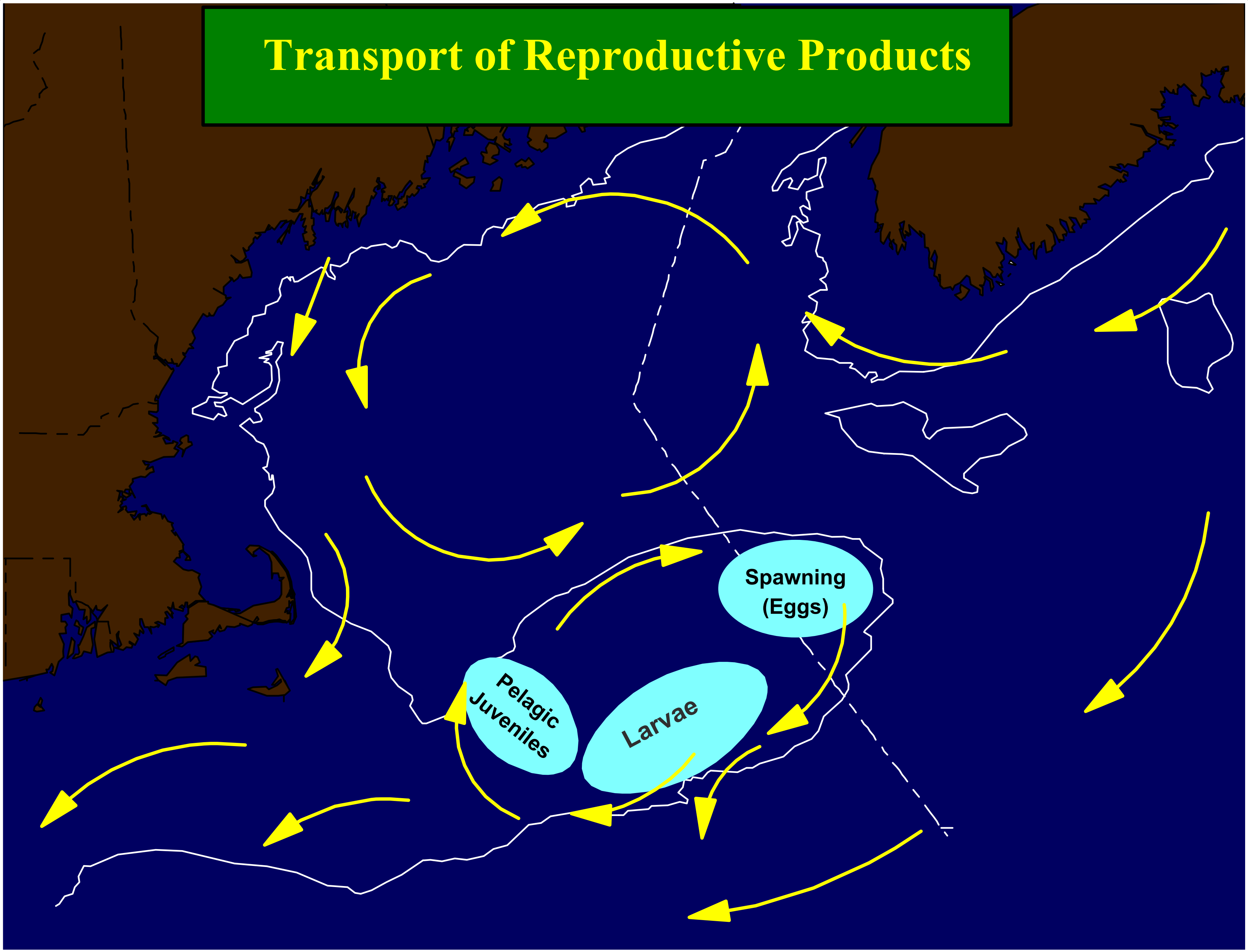
Longitude
-76
-74
-72
-70
-68
-66
42.5
41.2
39.9
38.6
37.3
36.0
JUL 1999
Jul 1999
Longitude



Area II Reporting Locations: Weeks 31-32
41.5
41.4
41.3
41.2
41.1
41.0
-67.50
-67.25
-67.00
-66.75
-66.50
-66.25
Longitude (deg)
> 2500 lb/day
1850-2500 lb/day
1500-1850 lb/day
1100-1500 lb/day
< 1100 lb/day


Georges Bank Haddock
Age 0 (<20 cm), Autumn Surveys
Number of Age 0 haddock per 30 minute Haul
0
10
20
30
40
80
120
160
1963
Year class
2003
Year class
1965
1970
1975
1980
1985
1990
1995
2000
2005
Year of Autumn Survey

Transport of Reproductive Products



Bases for Tradeoffs

- Scallop Biology
- Fishery and Fleet Dynamics
- Economics:
- Management Experiments
- Habitat Issues
- **Better Surveys and Better Tools**
  - **Improved survey estimation methods: Research, Commercial, Video**
  - **Dynamic Simulation models for evaluation of alternatives**
    - **Slight differences among constant and rotational strategies implies selection among alternatives can address habitat concepts without scallop yield penalty**
  - **GIS tools for specification of Areas**
  - **Optimization Methods**

Bases for Tradeoffs

- Scallop Biology
- **Fishery and Fleet Dynamics**
  - **Reallocation of Effort**
  - **Spatial Concentration of Fisheries**
  - **Crew constraints imply upper bound on daily harvest rate**
  - **Effects of weather**
- Economics:
- Management Experiments
- Habitat Issues
- Better Surveys and Better Tools